Tensions in Cosmology:
Are we Approaching New Physics?

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IHEP, Beijing July 2025

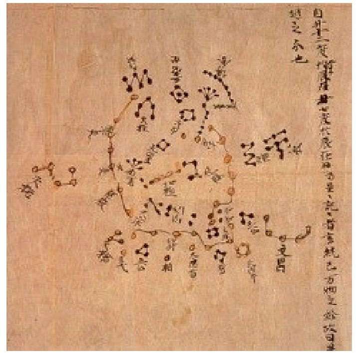
- The history of Science is a history of tensions between theoretical predictions and observations

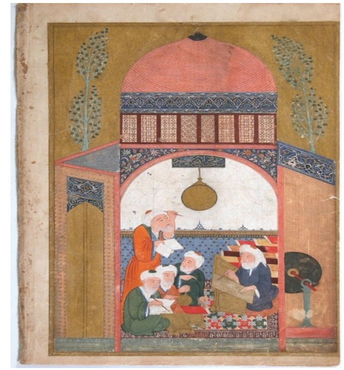
- Astrophysics and Cosmology have become precision sciences with an incredibly huge amount of data

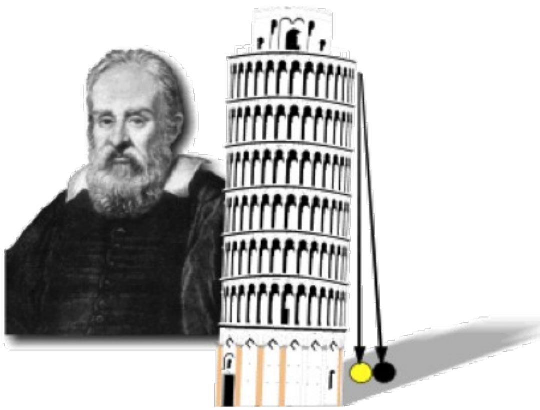
- New Tensions appear.

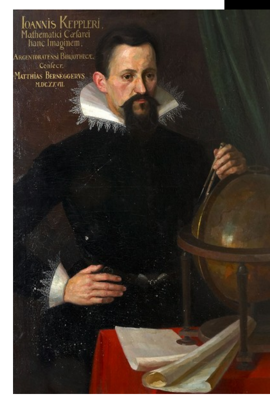
  Are we approaching New Physics?

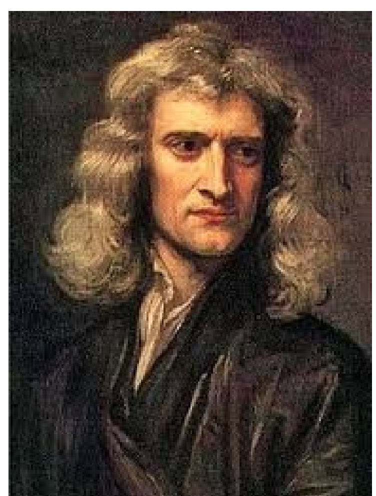
History of Science - History of Tensions





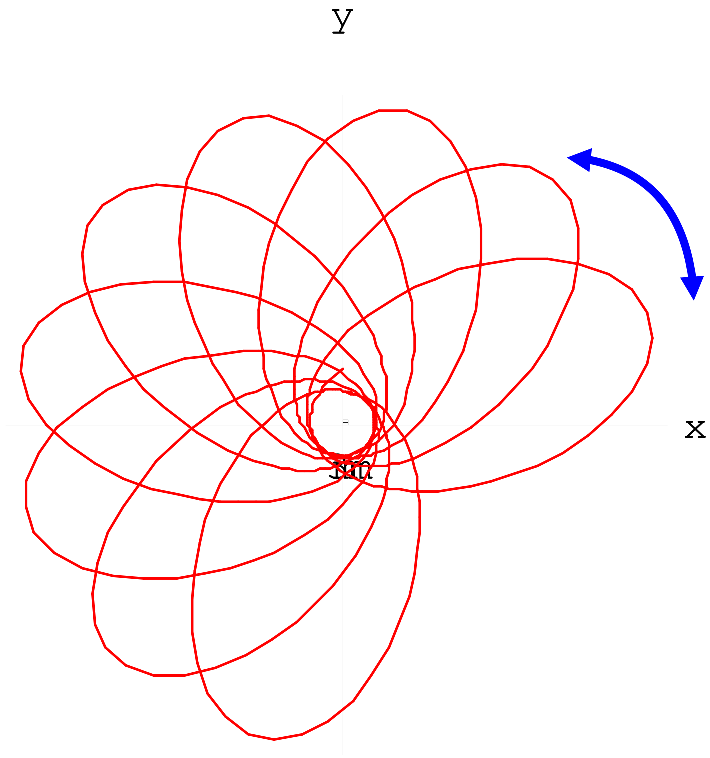






Mercury periliheimum - 1859

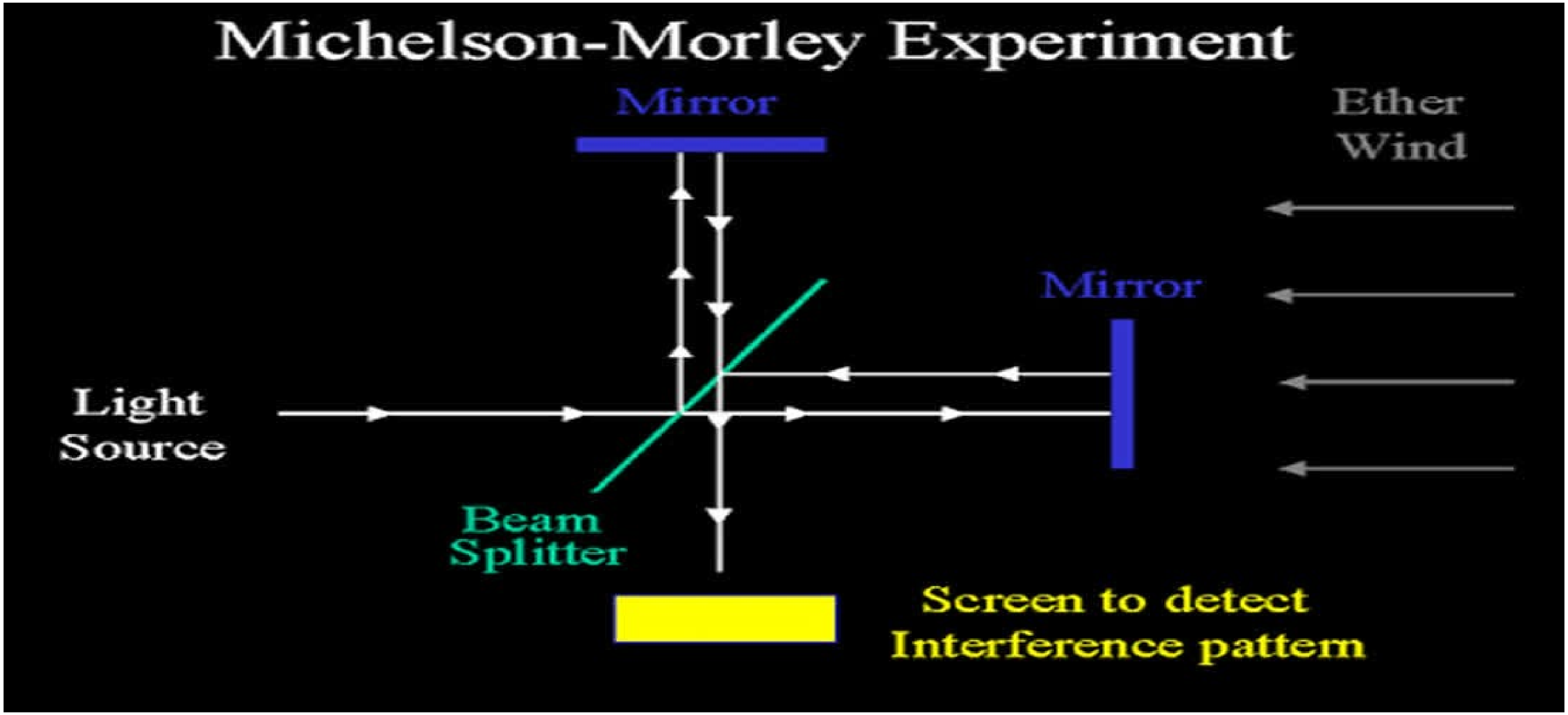
- The true orbits of planets, even if seen from the SUN are not ellipses. They are rather curves of this type:



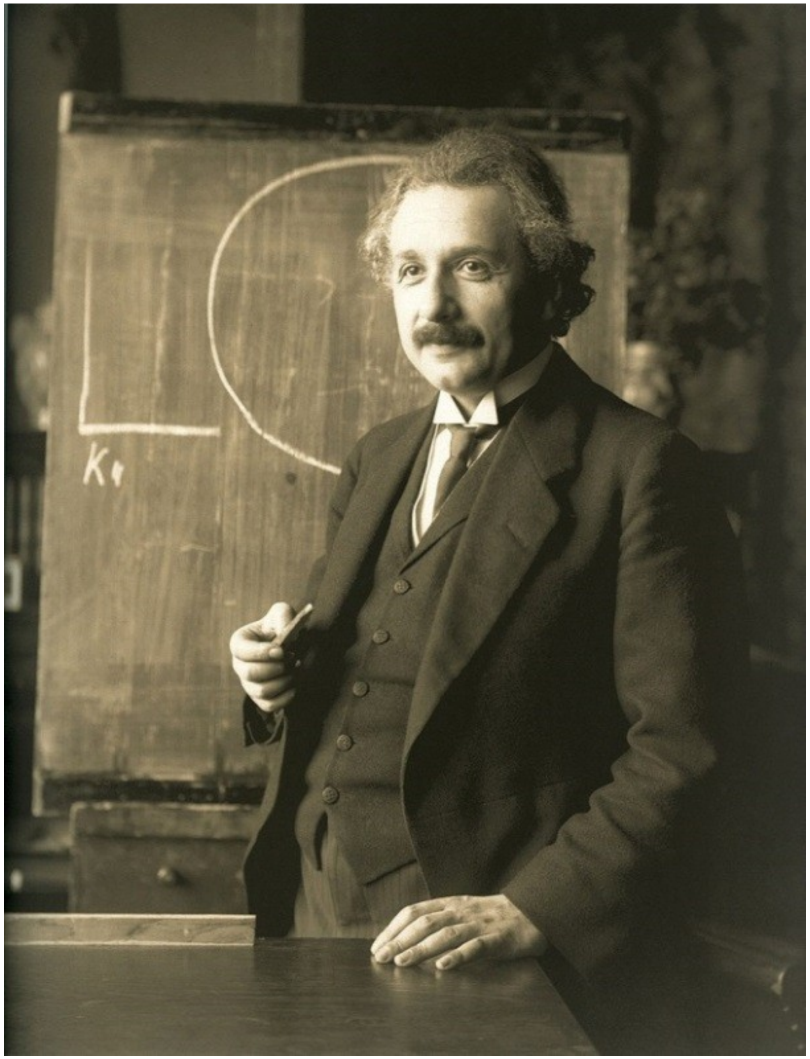
For the planet Mercury it is

$$\Delta\varphi = 43''\ of\ arc\ per\ century$$

Michelson–Morley experiment - 1887



The Theory of Relativity

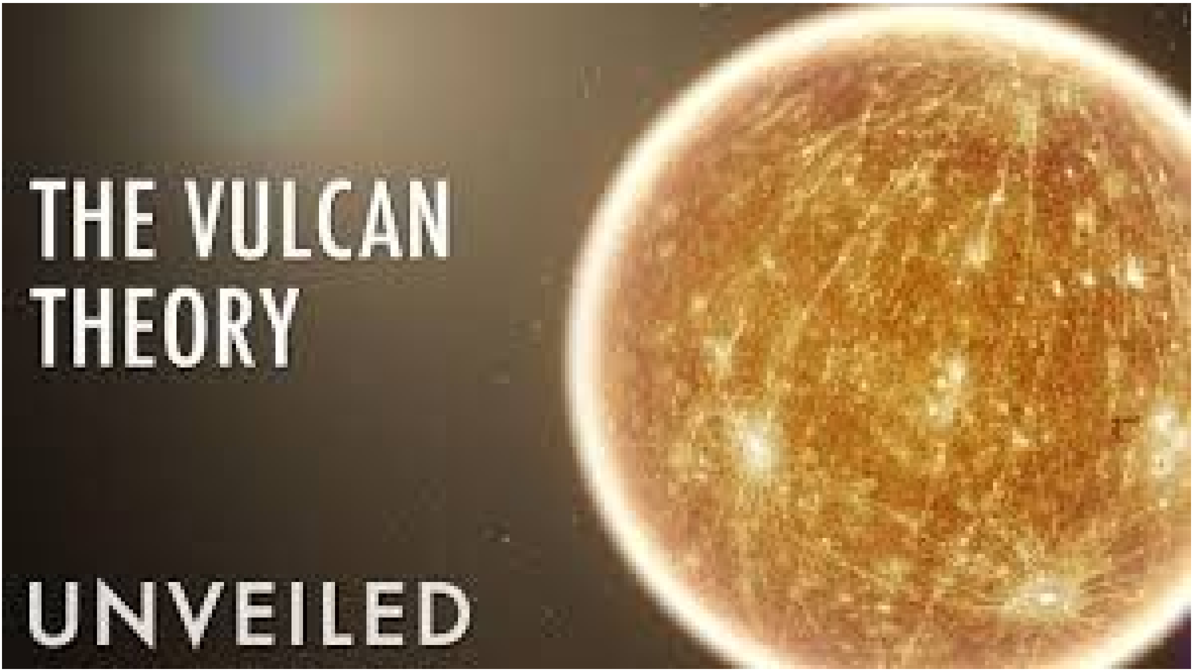


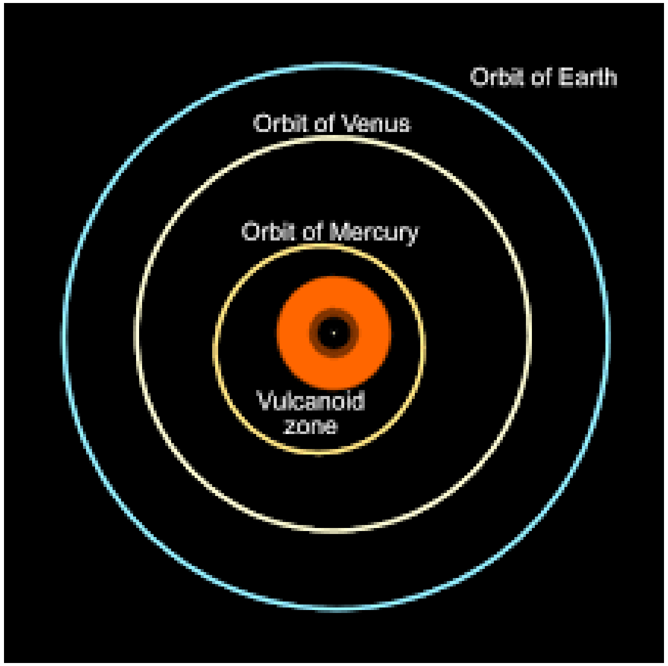
$$S=\frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R-2\Lambda\right]+\int d^4xL_m\left(g_{\mu\nu},\psi\right)$$

$$\Rightarrow R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R+g_{\mu\nu}\Lambda=8\pi GT_{\mu\nu}$$

$$T^{\mu\nu}\equiv\frac{2}{\sqrt{-g}}\frac{\delta L_m}{\delta g_{\mu\nu}}$$

60 years of tension





Modified Gravity before General Relativity

- Modifications to Newton's Law
- Inverse Cube Law.
- Extended Inverse-Square Law (Simon Newcomb - 1880’s)
- Lord Kelvin - theory of everything (end of 19th century)
- Hendrik Lorentz: gravity on the basis of his ether theory and Maxwell's equations. (1900)
- Nordström's theory of gravitation (1912 and 1913)
- Einstein's scalar theory of gravity (1913)

History of Major Shifts of Cosmological Models

Aristarchus of Samos (c. 310-230 BCE)

- **Geocentric (Ptolemy) to Heliocentric (Copernicus, 16th-17th c.):**
  - Retrograde motion (Copernicus)
  - Phases of Venus, Moons of Jupiter (Galileo, 1610)
- **Heliocentric to Infinite Universe (18th-19th c.):**
  - Improved telescopes, Uranus discovery (Herschel, 1781)
  - Stellar parallax (Bessel, 1838)
- **Infinite to Static Universe (Einstein, early 20th c.):**
  - Nebulae spectroscopy (Slipher)
  - Stellar distances (Leavitt, Hertzsprung)
- **Static to Expanding Universe (Lemaître, Hubble, 1920s-30s):**
  - Galactic redshift (Slipher, 1912-14)
  - Hubble's law (Hubble, 1929)
- **Expanding Universe to Inflationary Big Bang (1960s-80s):**
  - CMB (Penzias & Wilson, 1964)
  - Light element abundance (Alpher, Herman)
  - Inflation theory (Guth, Linde, 1980s)
- **Introduction of Dark Matter (1970s-80s):**
  - Galaxy rotation curves (Rubin, 1970s)
  - Gravitational lensing (Walsh et al., 1979)
  - Galaxy clusters (Zwicky, 1930s)
- **Lambda-CDM (late 1990s-present):**
  - Supernova observations (Perlmutter, Schmidt, Riess, 1998-99)
  - CMB (WMAP, Planck), BAO (SDSS, 2005)
- **Potential Future Shift (2020s-?):**
  - Hubble tension (Riess et al. vs Planck Collaboration)
  - S8 (growth rate) tension (KiDS, DES, Planck collaborations)
  - Cosmic dipoles tension (Various teams)
  - CMB anomalies (Planck Collaboration)
  - ISW (Integrated Sachs-Wolfe) tension
  - Lithium problem (Primordial Nucleosynthesis)

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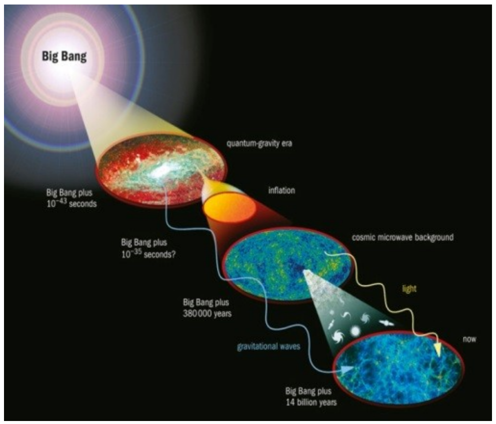
New Astronomy Reviews

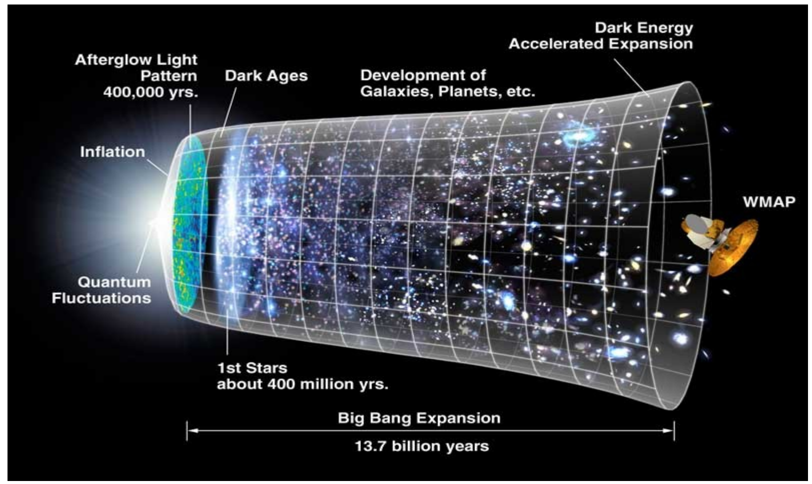
Volume 95, December 2022, 101659

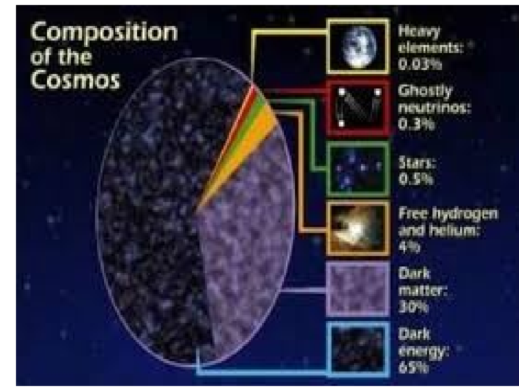
Challenges for ΛCDM: An update

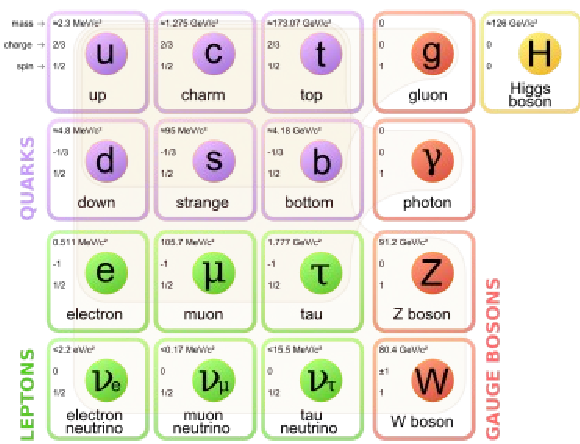
L. Perivolaropoulos, F. Skara

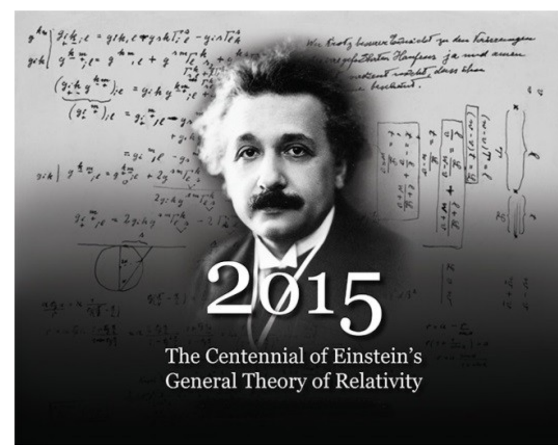
Summary of 20th century Observations



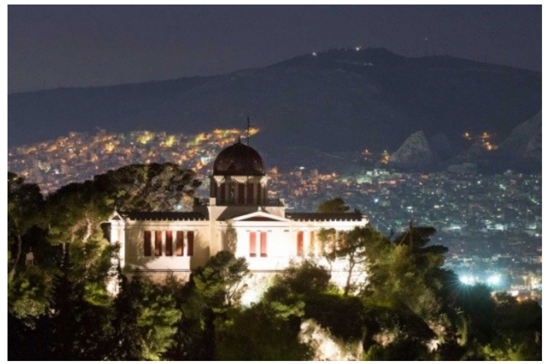


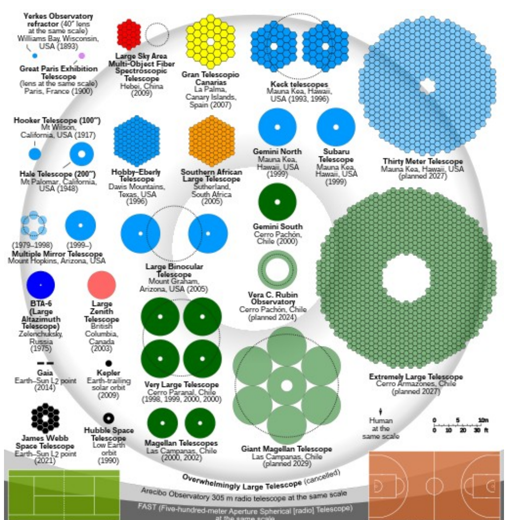


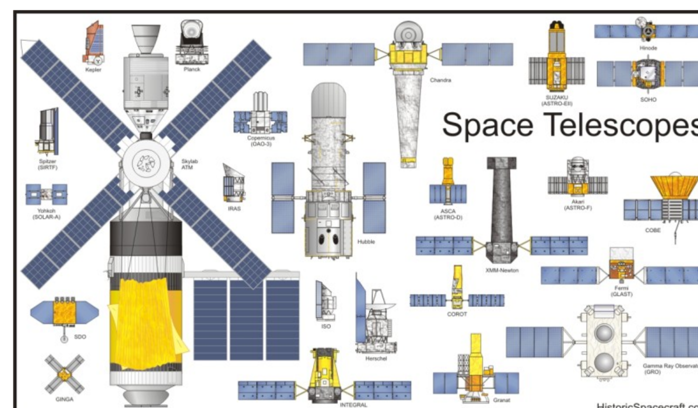




Astrophysics and Cosmology in the 21st century



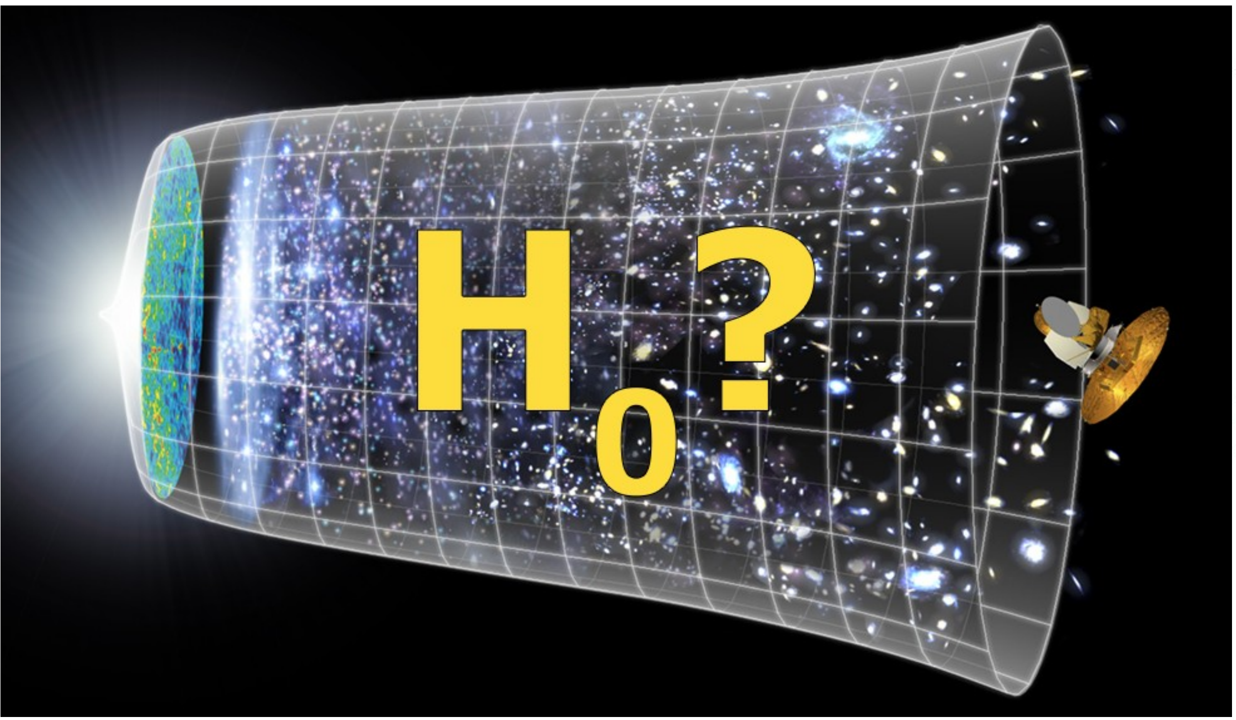


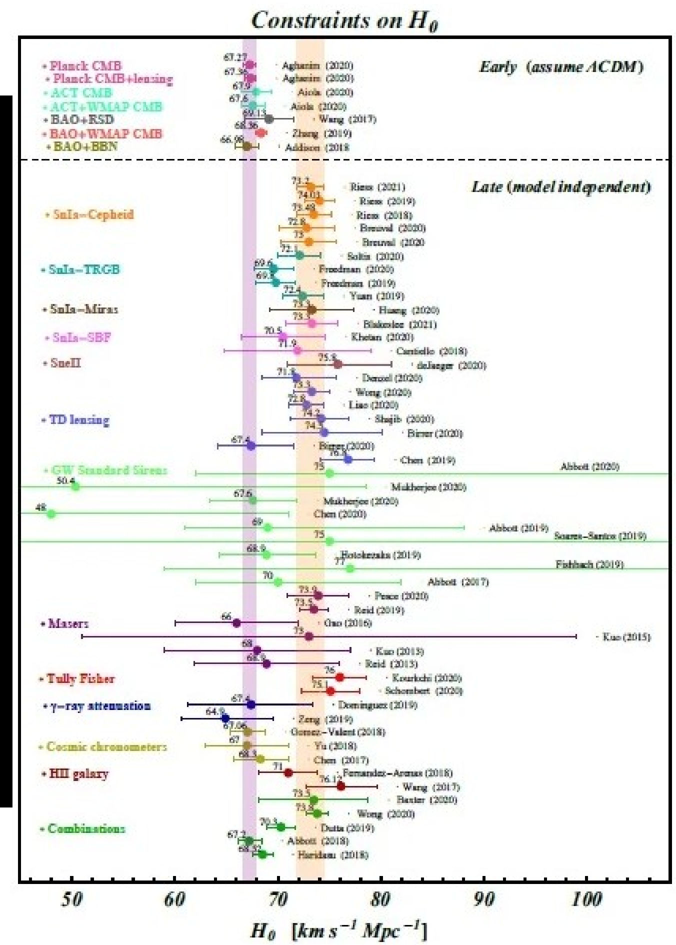


So what do these new observations tell us?

H0 tension

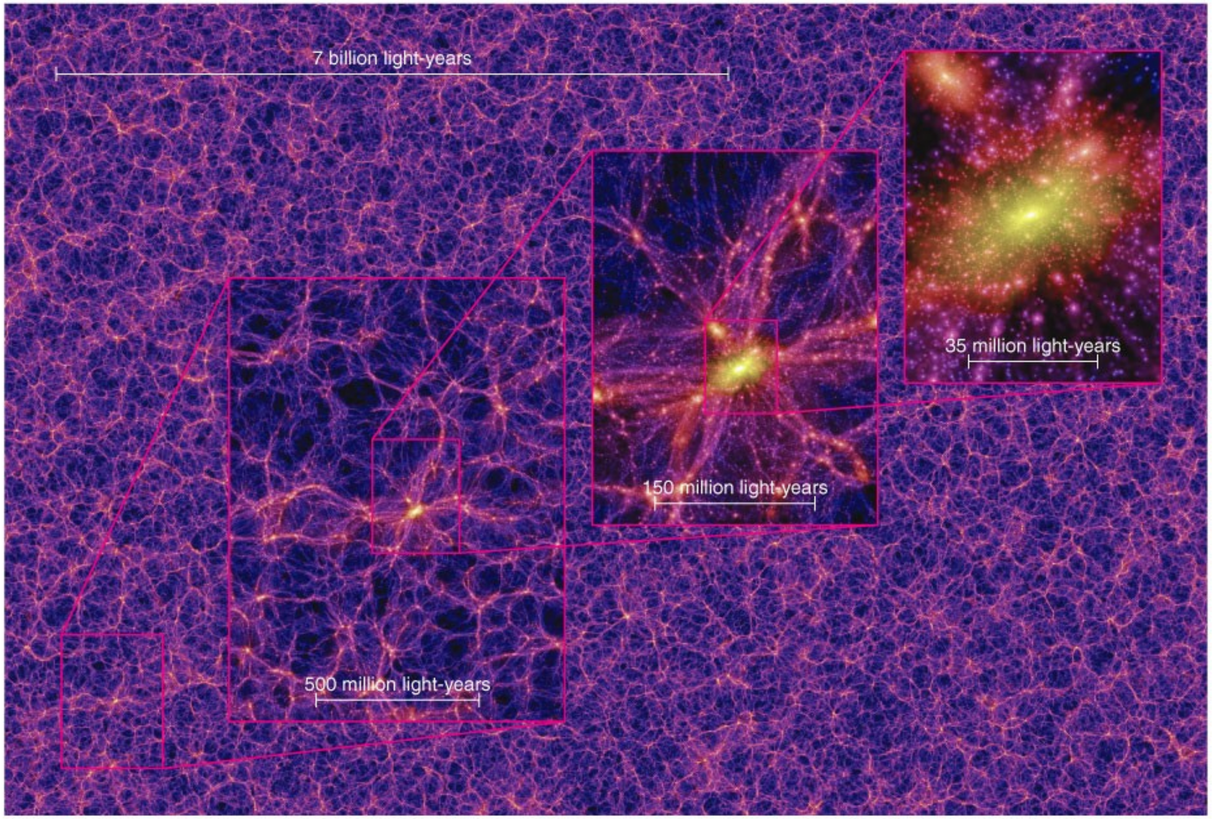
- The Universe expands faster than expected!

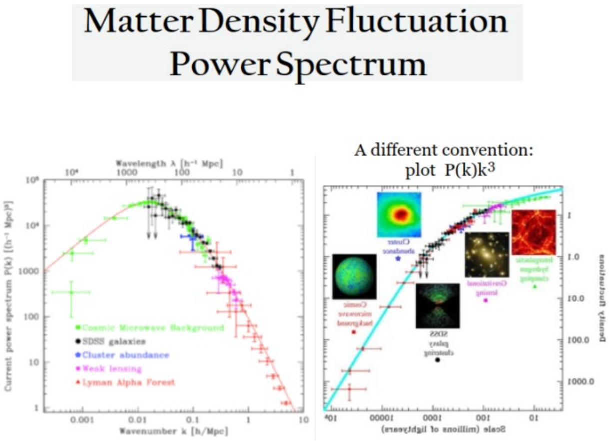




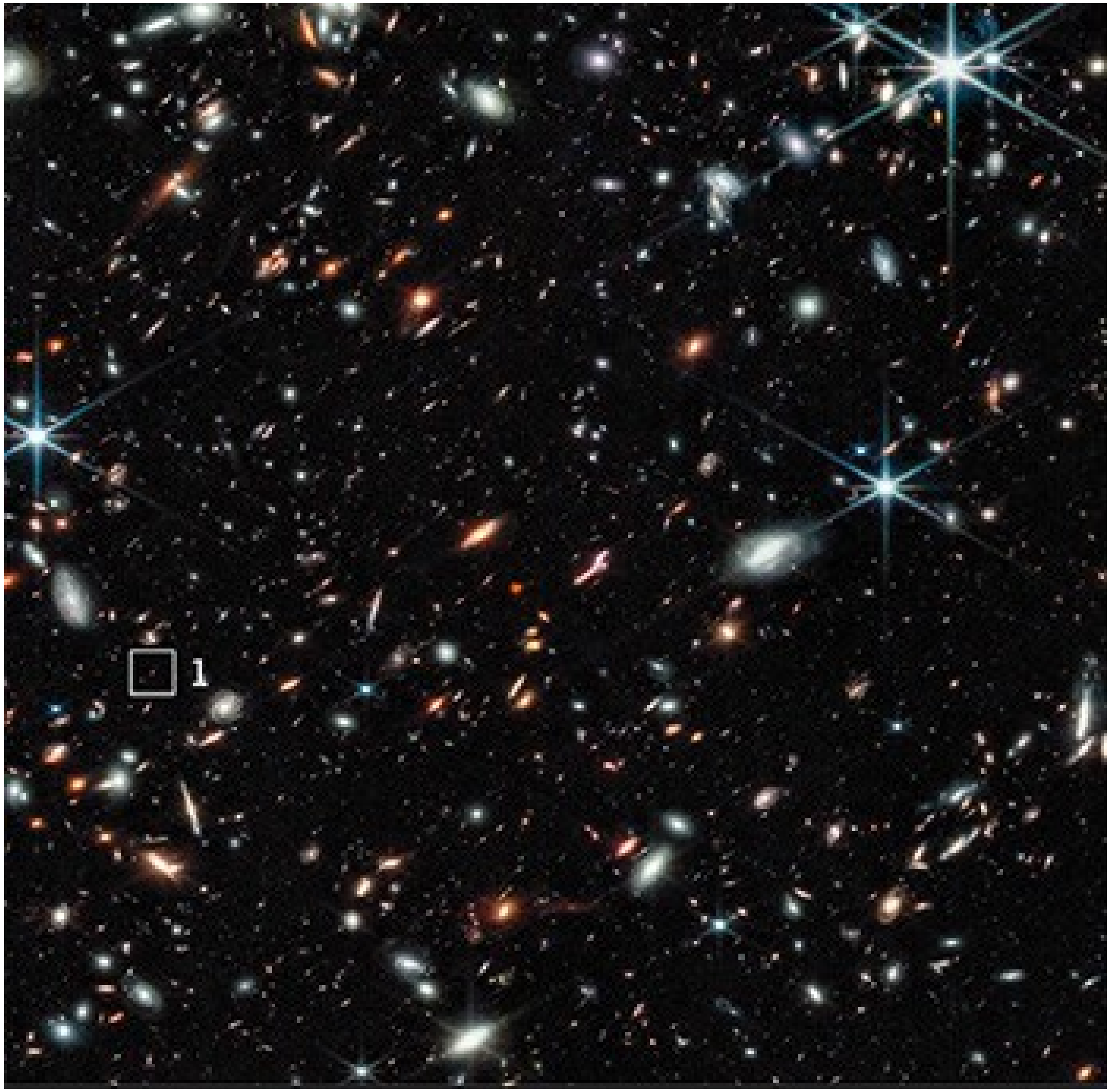
S8 Tension

- “Less” Matter clustering than expected!



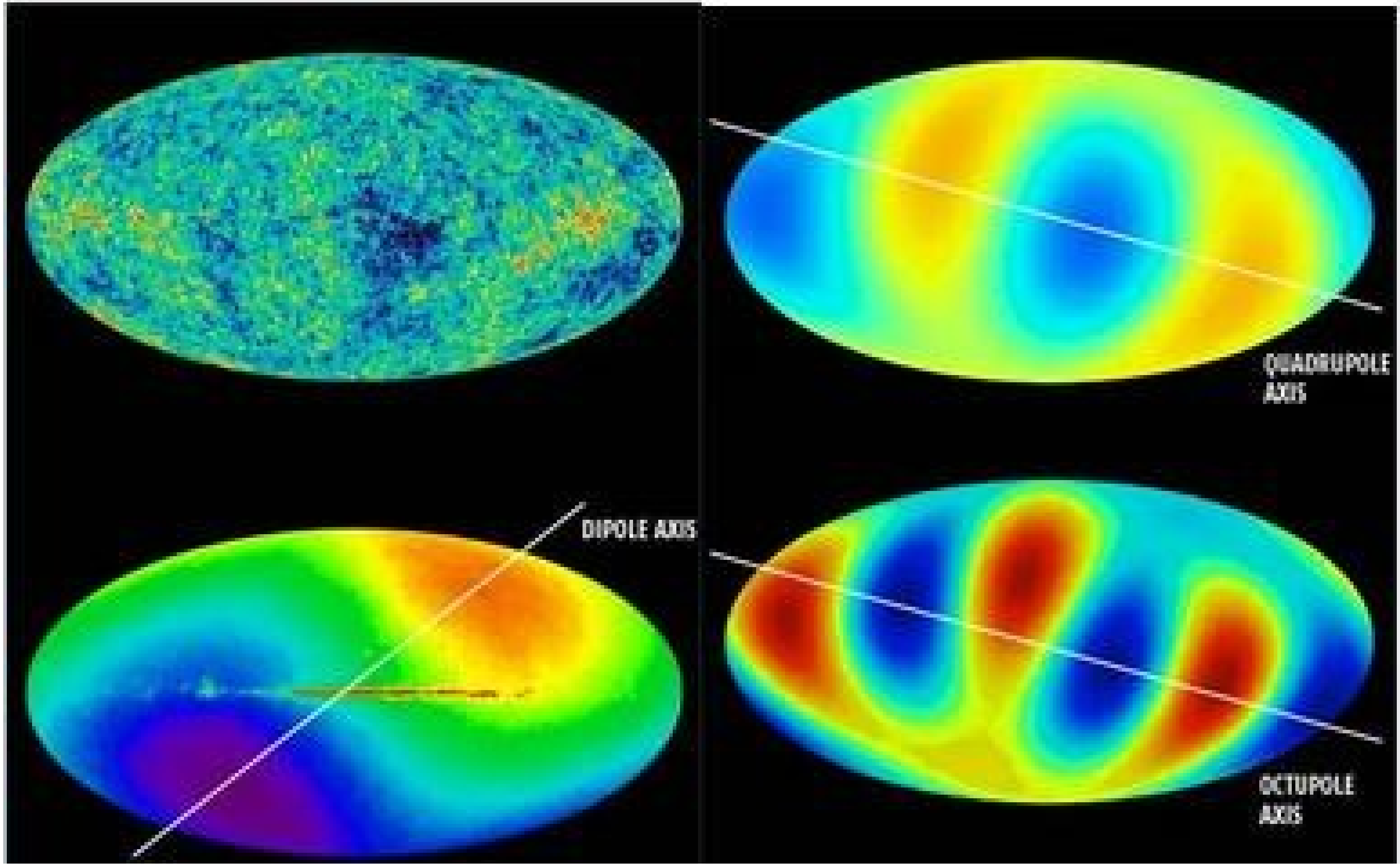


Too many galaxies too early!



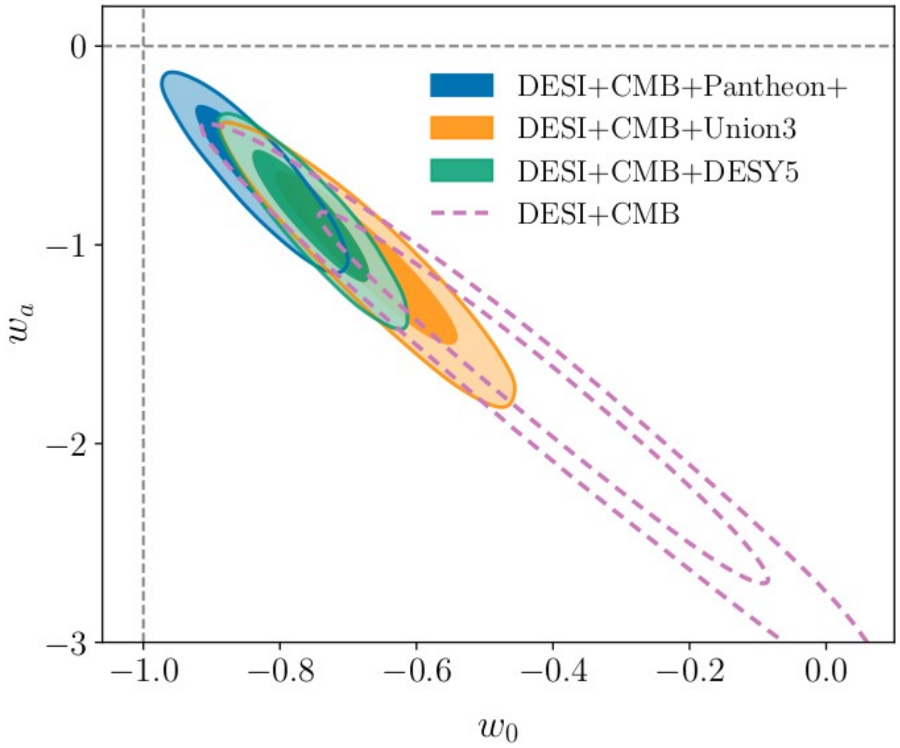
James Webb space telescope

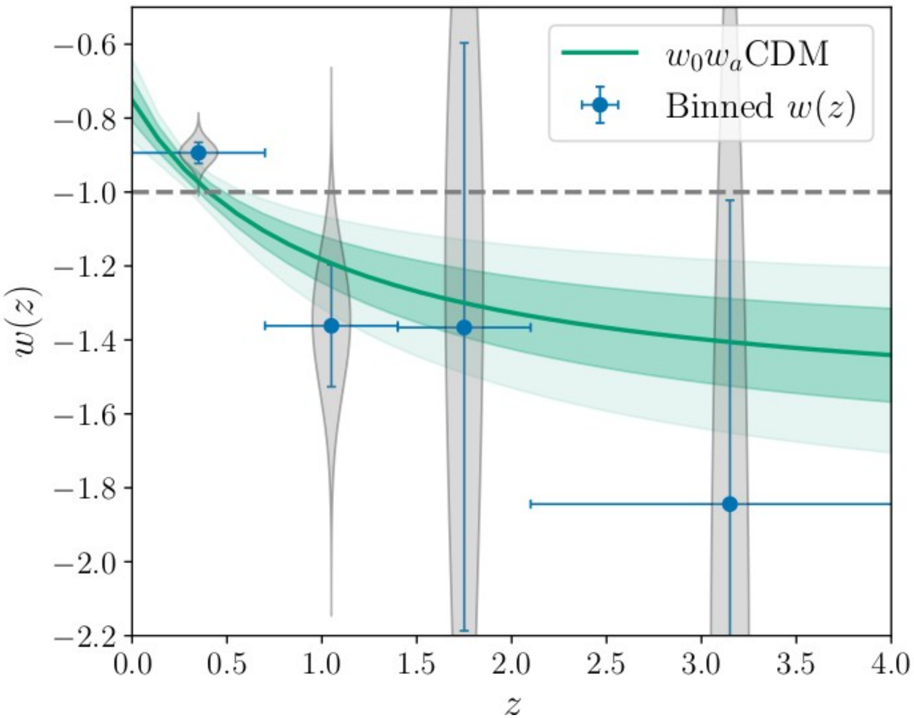
Cosmic dipole tension!



The lensing anomaly

DESI2 DATA and QUINTOM BEHAVIOR





Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Cosmology Intertwined:
A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies

Elcio Abdalla,[1] Guillermo Franco Abellán,[2] Amin Aboubrahim,[3] Adriano Agnello,[4] Özgür Akarsu,[5] Yashar Akrami,[6,7,8,9] George Alestas,[10] Daniel Aloni,[11] Luca Amendola,[12] Luis A. Anchordoqui,[13,14,15] Richard I. Anderson,[16] Nikki Arendse,[17] Marika Asgari,[18,19] Mario Ballardini,[20,21,22,23] Vernon Barger,[24] Spyros Basilakos,[25,26] Ronaldo C. Batista,[27] Elia S. Battistelli,[28,29] Richard Battye,[30] Micol Benetti,[31,32] David Benisty,[33,34,35] Asher Berlin,[36] Paolo de Bernardis,[28,29] Emanuele Berti,[37] Bohdan Bidenko,[38,39] Simon Birrer,[40] John P. Blakeslee,[41] Kimberly K. Boddy,[42] Clecio R. Bom,[43,44] Alexander Bonilla,[45] Nicola Borghi,[46,47] François R. Bouchet,[48] Matteo Braglia,[49,21] Thomas Buchert,[50] Elizabeth Buckley-Geer,[51,52] Erminia Calabrese,[53] Robert R. Caldwell,[54] David Camarena,[55] Salvatore Capozziello,[56,31] Stefano Casertano,[57] Angela Chen,[58,59] Geoff C.-F. Chen,[60] Hsin-Yu Chen,[61] Jens Chluba,[30] Anton Chudaykin,[62] Michele Cicoli,[20,22] Craig J. Copi,[6] Fred Courbin,[16] Francis-Yan Cyr-Racine,[63] Bożena Czerny,[64] Maria Dainotti,[65,66,67] Guido D'Amico,[68,69] Anne-Christine Davis,[33,34] Javier de Cruz Pérez,[70] Jaume de Haro,[71] Jacques Delabrouille,[72,73,74,75] Peter B. Denton,[76] Suhail Dhawan,[77] Keith R. Dienes,[78,79] Eleonora Di Valentino,[80,*] Pu Du,[81] Dominique Eckert,[82] Celia Escamilla-Rivera,[83] Agnès Ferté,[84] Fabio Finelli,[85,22] Pablo Fosalba,[86,87] Wendy L. Freedman,[52] Noemi Frusciante,[88] Enrique Gaztañaga,[86,87] William Giarè,[89,29] Elena Giusarma,[90] Adrià Gómez-Valent,[91] Will Handley,[92,93] Ian Harrison,[94] Luke Hart,[30] Dhiraj Kumar Hazra,[95] Alan Heavens,[7] Asta Heinesen,[50] Hendrik Hildebrandt,[96] J. Colin Hill,[97,98] Natalie B. Hogg,[99] Daniel E. Holz,[52,100,101] Deanna C. Hooper,[102] Nikoo Hosseininejad,[103] Dragan Huterer,[104,105] Mustapha Ishak,[106] Mikhail M. Ivanov,[107] Andrew H. Jaffe,[7] In Sung Jang,[52] Karsten Jedamzik,[108] Raul Jimenez,[109,110] Melissa Joseph,[11] Shahab Joudaki,[111,112] Marc Kamionkowski,[37] Tanvi Karwal,[113] Lavrentios Kazantzidis,[10] Ryan E. Keeley,[114] Michael Klasen,[3] Eiichiro Komatsu,[115,116] Léon V.E. Koopmans,[117] Suresh Kumar,[118] Luca Lamagna,[28,29] Ruth Lazkoz,[119] Chung-Chi Lee,[120] Julien Lesgourgues,[121] Jackson Levi Said,[122,123] Tiffany R. Lewis,[124] Benjamin L'Huillier,[125] Matteo Lucca,[126] Roy Maartens,[23,127,128] Lucas M. Macri,[129] Danny Marfatia,[130] Valerio Marra,[131,132,133] Carlos J. A. P. Martins,[134,135] Silvia Masi,[28,29] Sabino Matarrese,[136,137,138,139] Arindam Mazumdar,[140] Alessandro Melchiorri,[28,29] Olga Mena,[141] Laura Mersini-Houghton,[142] James Mertens,[143] Dinko Milaković,[133,132,144] Yuto Minami,[145] Vivian Miranda,[146] Cristian Moreno-Pulido,[147] Michele Moresco,[46,47] David F. Mota,[148] Emil Mottola,[63] Simone Mozzon,[149] Jessica Muir,[150] Ankan Mukherjee,[151] Suvodip Mukherjee,[150] Pavel Naselsky,[152] Pran Nath,[153] Savvas Nesseris,[99] Florian Niedermann,[154] Alessio Notari,[155] Rafael C. Nunes,[156] Eoin Ó Colgáin,[157,158] Kayla A. Owens,[52] Emre Özülker,[5] Francesco Pace,[159,160] Andronikos Paliathanasis,[161,162] Antonella Palmese,[163] Supriya Pan,[164] Daniela Paoletti,[85,22] Santiago E. Perez Bergliaffa,[165] Leandros Perivolaropoulos,[10] Dominic W. Pesce,[166,167] Valeria Pettorino,[168] Oliver H. E. Philcox,[169,107] Levon Pogosian,[170] Vivian Poulin,[2] Gaspard Poulot,[80] Marco Raveri,[171] Mark J. Reid,[172] Fabrizio Renzi,[173] Adam G. Riess,[37] Vivian I. Sabla,[54] Paolo Salucci,[174,175] Vincenzo Salzano,[176] Emmanuel N. Saridakis,[26,75,177] Bangalore S. Sathyaprakash,[178,179,94] Martin Schmaltz,[11] Nils Schöneberg,[180] Dan Scolnic,[181] Anjan A. Sen,[182,183] Neelima Sehgal,[184] Arman Shafieloo,[185] M.M. Sheikh-Jabbari,[186] Joseph Silk,[187] Alessandra Silvestri,[173] Foteini Skara,[10] Martin S. Sloth,[188] Marcelle Soares-Santos,[58] Joan Solà Peracaula,[147] Yu-Yang Songsheng,[81] Jorge F. Soriano,[13,14] Denitsa Staicova,[189] Glenn D. Starkman,[6,7] István Szapudi,[190] Elsa M. Teixeira,[80] Brooks Thomas,[191] Tommaso Treu,[60] Emery Trott,[58] Carsten van de Bruck,[80] J. Alberto Vazquez,[192] Licia Verde,[193,194] Luca Visinelli,[195] Deng Wang,[196] Jian-Min Wang,[81] Shao-Jiang Wang,[197] Richard Watkins,[198] Scott Watson,[199] John K. Webb,[120] Neal Weiner,[200] Amanda Weltman,[201] Samuel J. Witte,[202] Radosław Wojtak,[4] Anil Kumar Yadav,[203] Weiqiang Yang,[204] Gong-Bo Zhao,[205,206] and Miguel Zumalacárregui[207]

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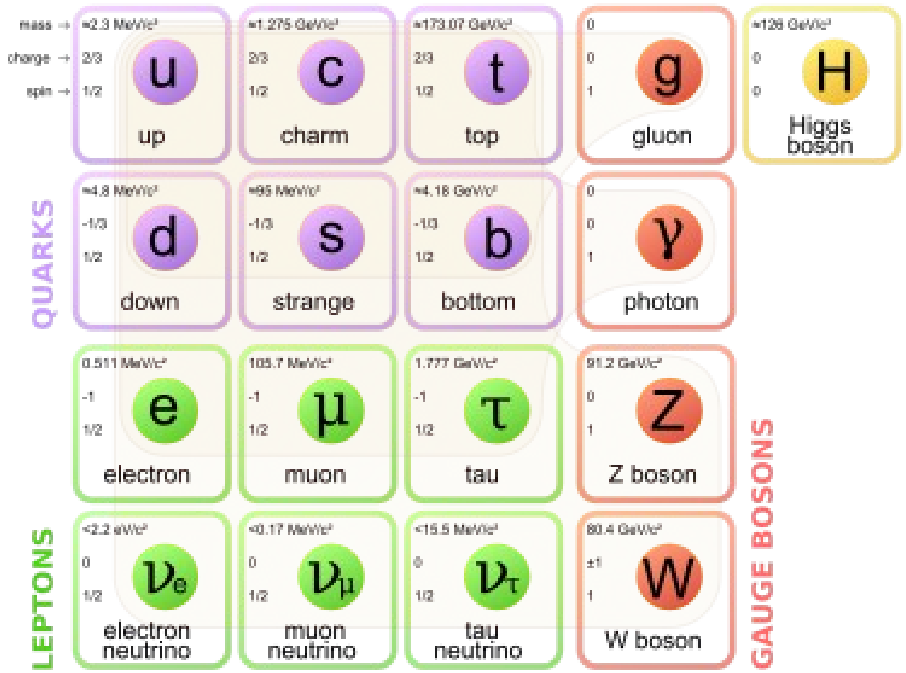
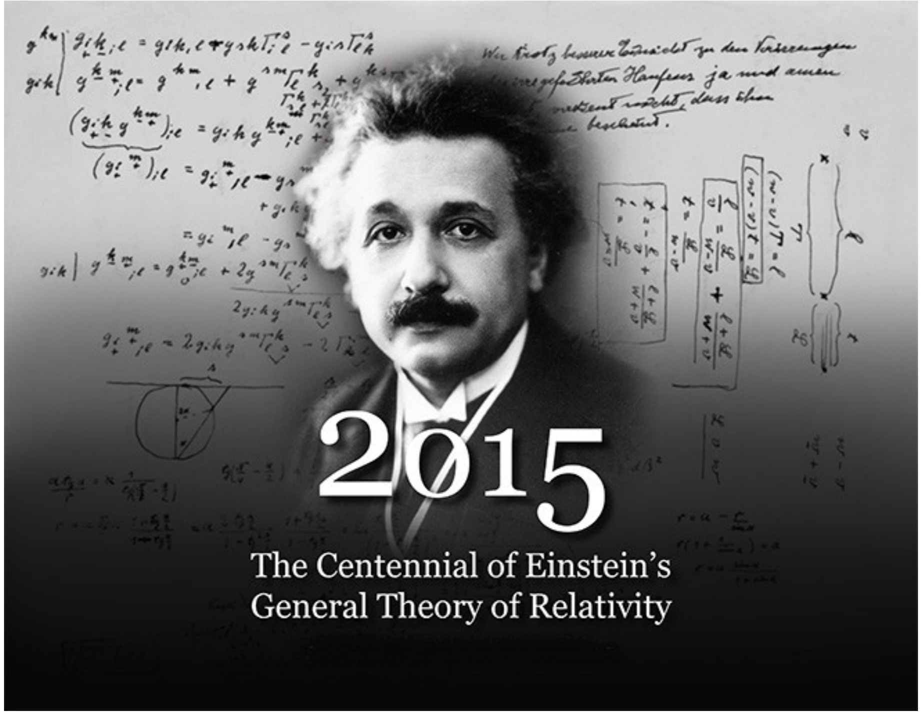
THE NEW CRISIS
IN COSMOLOGY
PBS

Are we approaching a Revolution in Physics?

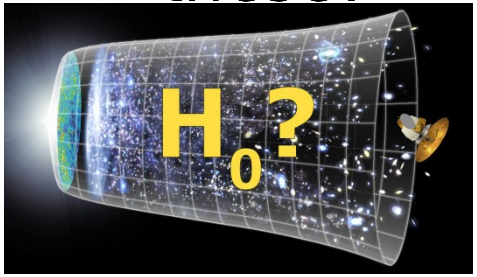
Knowledge of Physics: Standard Model + General Relativity

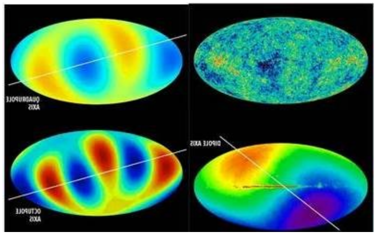


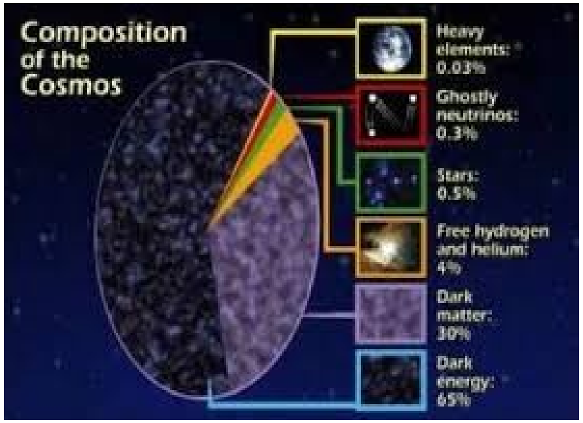


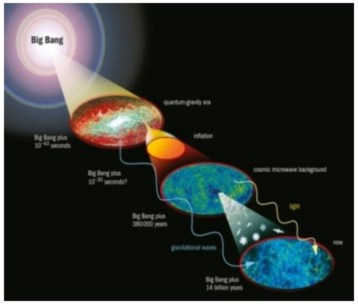
Are we approaching a Revolution in Physics?

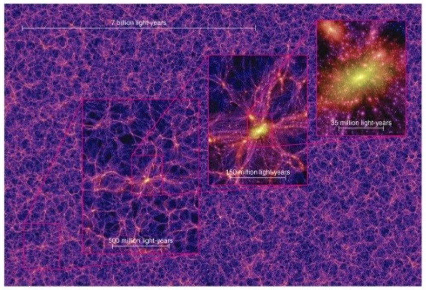
So can our knowledge of Physics describes all these?











NO! We need new physics!

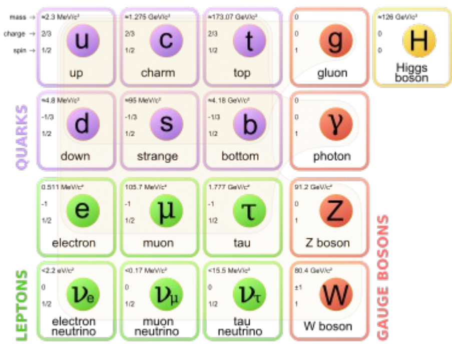
We need to modify something:

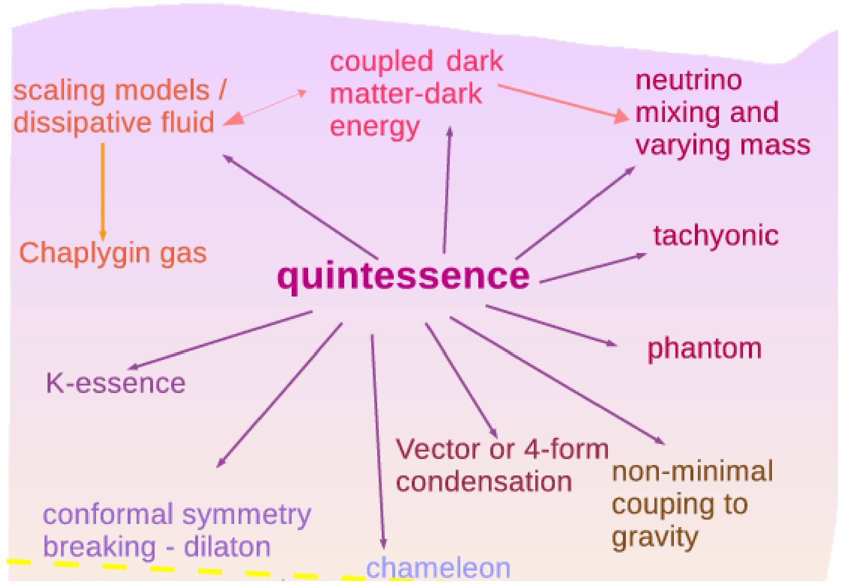
The universe content

or

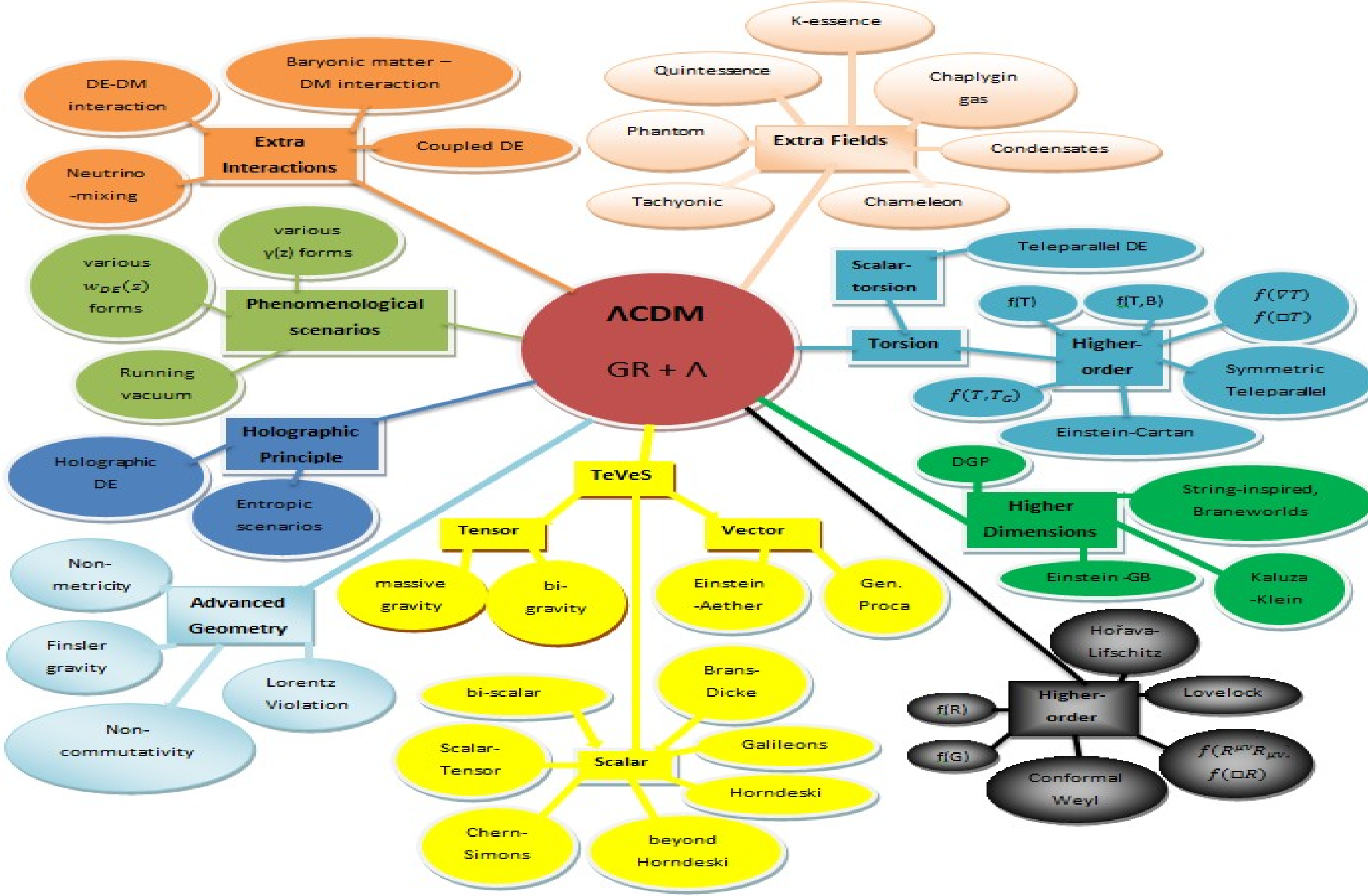
The theory of Gravity

New particles/interactions





Modified Gravity



Standard Model vs General Relativity

1

$$\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -
\end{gathered}$$

2

$$\begin{gathered}
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -
\end{gathered}$$

3

$$\begin{gathered}
\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 + \gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] -
\end{gathered}$$

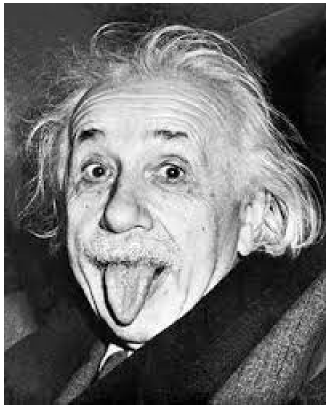
4

$$\begin{gathered}
\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1 + \gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -
\end{gathered}$$

5

$$\begin{gathered}
\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}$$

$$S = -\frac{1}{16\pi G}\int \sqrt{-g}(R(g) + 2\Lambda)\,\mathrm{d}^4x$$



General Relativity Assumptions and Considerations

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R - 2\Lambda\right] + \int d^4x\, L_m\left(g_{\mu\nu}, \psi\right)$$

- Diffeomorphism invariance
- Spacetime dimensionality=4
- Geometry=Curvature (connection=Levi Civita)
- Linear in Ricci scalar
- Metric compatibility (zero non-metricity)
- Minimal matter coupling
- Equivalence principle
- Lorentz invariance
- Locality

"Those that do not know geometry are not allowed to enter".

Front Door of Plato's Academy

Descriptions of Gravity

- Einstein 1916: **General Relativity**:

  energy-momentum source of spacetime Curvature

  Levi-Civita connection: Zero Torsion

- Einstein 1928: **Teleparallel Equivalent of GR:**

  Weitzenbock connection: Zero Curvature

[Cai, Capozziello, De Laurentis, Saridakis, Rept.Prog.Phys. 79]

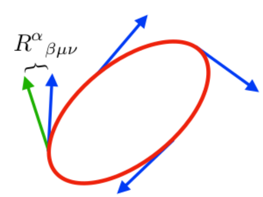
$$\left\{ {\alpha \atop \mu\nu} \right\} = \frac{1}{2} g^{\alpha\lambda} \big(g_{\lambda\nu,\mu} + g_{\mu\lambda,\nu} - g_{\mu\nu,\lambda} \big). \tag{1.3}$$

The corresponding covariant derivative will be denoted by $\mathcal{D}$ so that we will have $\mathcal{D}_\alpha g_{\mu\nu} = 0$. A general connection $\Gamma^\alpha{}_{\mu\nu}$ then admits the following convenient decomposition:

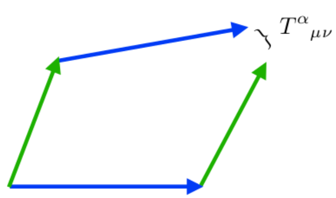
$$\Gamma^\alpha{}_{\mu\nu} = \left\{ {\alpha \atop \mu\nu} \right\} + K^\alpha{}_{\mu\nu} + L^\alpha{}_{\mu\nu} \tag{1.4}$$

with

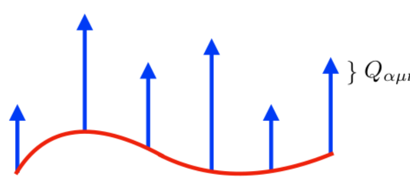
$$K^\alpha{}_{\mu\nu} = \frac{1}{2} T^\alpha{}_{\mu\nu} + T_{(\mu}{}^{\alpha}{}_{\nu)}\,, \quad L^\alpha{}_{\mu\nu} = \frac{1}{2} Q^\alpha{}_{\mu\nu} - Q_{(\mu}{}^{\alpha}{}_{\nu)} \tag{1.5}$$



The rotation of a vector transported along a closed curve is given by the curvature: General Relativity.



The non-closure of parallelograms formed when two vectors are transported along each other is given by the torsion: Teleparallel Equivalent of General Relativity.



The variation of the length of a vector as it is transported is given by the non-metricity: Symmetric Teleparallel Equivalent of General Relativity.

Metric-Affine Modified Gravity

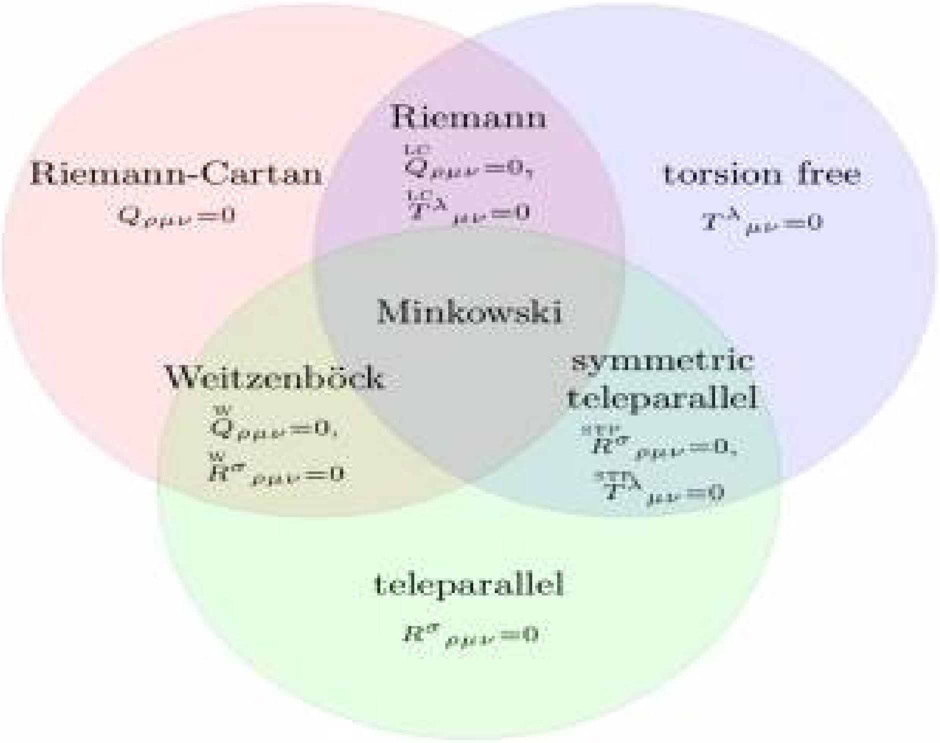


FIG. 1. Subclasses of metric-affine geometry, depending on the properties of connection.

$$S_{\rm GR} = \frac{1}{2\kappa^2}\int\left\{g^{\mu\nu}\hat{R}_{\mu\nu} + \lambda^{\mu\nu\lambda}_{(1)}T_{\mu\nu\lambda} + \lambda^{\mu\nu\lambda}_{(2)}Q_{\mu\nu\lambda}\right\}\sqrt{-g}\,d^4x\,,$$

$$S_{\rm total} = S_{\rm GR} + S_{\rm matter}\,,$$

Curvature and Torsion

- Vierbeins e_A^{μ} : four linearly independent fields in the tangent space
  $g_{\mu\nu}(x) = \eta_{AB}\; e_{\mu}^{A}(x)\;\; e_{\nu}^{B}(x)$
- Connection: ω_{ABC}
- Curvature tensor: $R^{A}_{B\mu\nu} = \omega^{A}_{B\nu,\mu} - \omega^{A}_{B\mu,\nu} + \omega^{A}_{C\mu}\omega^{C}_{B\nu} - \omega^{A}_{C\nu}\omega^{C}_{B\mu}$
- Torsion tensor: $T^{A}_{\mu\nu} = e^{A}_{\nu,\mu} - e^{A}_{\mu,\nu} + \omega^{A}_{B\mu}e^{B}_{\nu} - \omega^{A}_{B\nu}e^{B}_{\mu}$
- Levi-Civita connection and Contortion tensor: $\omega_{ABC} = \Gamma_{ABC} + K_{ABC}$

$$K_{ABC} = \frac{1}{2}\left(T_{CAB} - T_{BCA} - T_{ABC}\right) = -K_{BAC}$$

- Curvature and Torsion Scalars:

$$\boxed{R = \overline{R} + T - 2\left(T_{\nu}^{\ \nu\mu}\right)_{;\mu}}$$

$$R = g^{\mu\nu}R_{\mu\nu} = g^{\mu\nu}R^{\rho}_{\mu\rho\nu}$$

$$T = \frac{1}{4}T^{\rho\mu\nu}T_{\rho\mu\nu} + \frac{1}{2}T^{\rho\mu\nu}T_{\nu\mu\rho} - T^{\rho}_{\rho\mu}T^{\nu\mu}_{\nu}$$

f(T) Gravity and f(T) Cosmology

- f(T) Gravity: Simplest torsion-based modified gravity
- Generalize T to f(T) (inspired by f(R))

$$S = \frac{1}{16\pi G}\int d^4x\, e\,[T + f(T)] + S_m$$

- Equations of motion:

$$e^{-1}\partial_\mu\left(e e_A^\rho S_\rho^{\ \mu\nu}\right)(1+f_T) - e_A^\lambda T_{\ \mu\lambda}^\rho S_\rho^{\ \nu\mu} + e_A^\rho S_\rho^{\ \mu\nu}\partial_\mu(T) f_{TT} - \frac{1}{4}e_A^\nu[T + f(T)] = 4\pi G e_A^\rho \mathrm{T}_\rho^{\ \nu\{\mathrm{EM}\}}$$

- f(T) Cosmology: Apply in FRW geometry:

$$e_\mu^A = diag(1, a, a, a) \ \Rightarrow\ ds^2 = dt^2 - a^2(t)\delta_{ij}dx^i dx^j$$ (not unique choice)

- Friedmann equations:

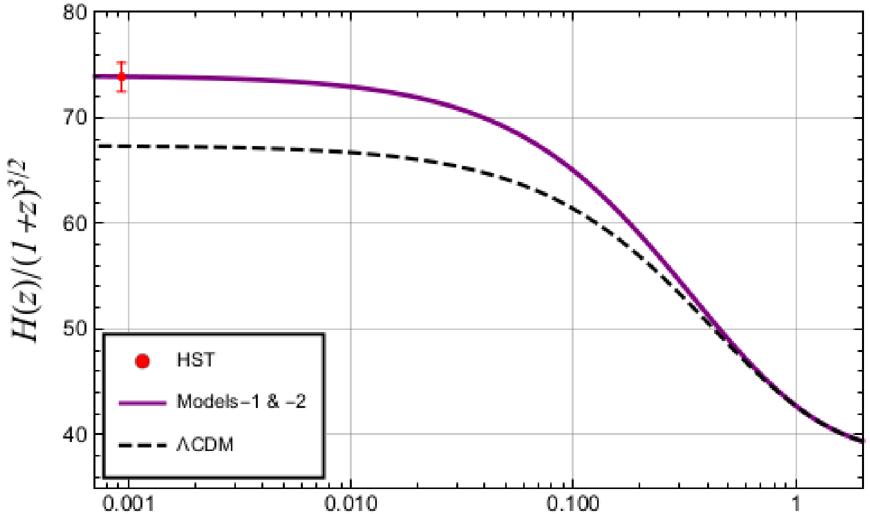
$$H^2 = \frac{8\pi G}{3}\rho_m - \frac{f(T)}{6} - 2f_T H^2$$

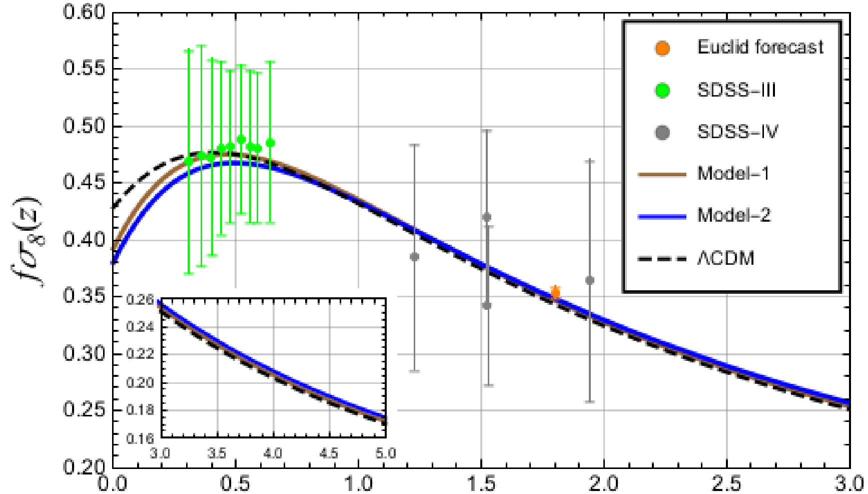
$$\dot{H} = -\frac{4\pi G(\rho_m + p_m)}{1 + f_T - 12H^2 f_{TT}}$$

- Find easily

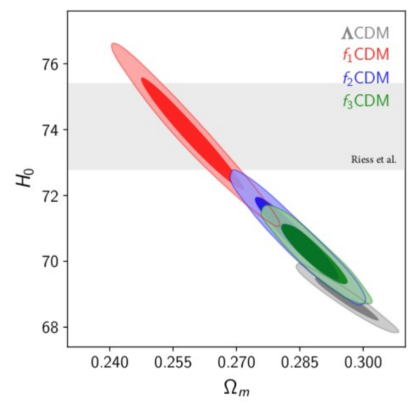
$$T = -6H^2$$

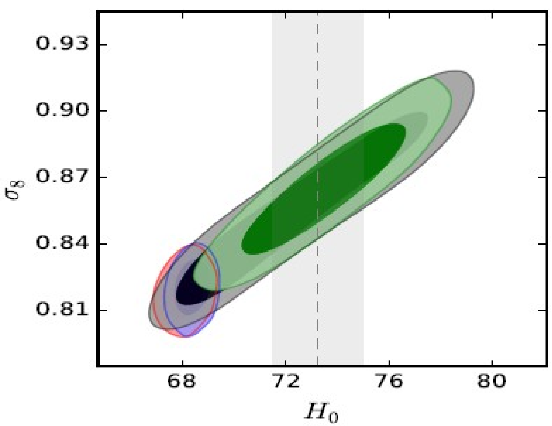
Solving H0 and S8 tensions in f(T) Gravity





Parameter	CMB + BAO	CMB + BAO + H_0
$10^2\omega_b$	$2.235^{+0.013}_{-0.013}$	$2.235^{+0.013}_{-0.013}$
ω_{cdm}	$0.1181^{+0.001}_{-0.001}$	$0.118^{+0.001}_{-0.001}$
$100\theta_s$	$1.041^{+0.00027}_{-0.00027}$	$1.041^{+0.00030}_{-0.00027}$
$\ln 10^{10}A_s$	$3.078^{+0.023}_{-0.023}$	$3.08^{+0.022}_{-0.022}$
n_s	$0.9678^{+0.0039}_{-0.0039}$	$0.9684^{+0.0039}_{-0.0044}$
τ_{reio}	$0.073^{+0.012}_{-0.013}$	$0.075^{+0.012}_{-0.012}$
n	$0.0043^{+0.0033}_{-0.0039}$	$0.0054^{+0.0020}_{-0.0020}$
$\log\alpha$	$10.00^{+0.081}_{-0.12}$	$10.03^{+0.06}_{-0.06}$
Ω_{F0}	$0.73^{+0.021}_{-0.028}$	$0.738^{+0.015}_{-0.015}$
H_0	$72.4^{+3.3}_{-4.1}$	$73.5^{+2.1}_{-2.1}$
σ_8	$0.855^{+0.023}_{-0.033}$	$0.866^{+0.02}_{-0.02}$
$\chi^2_{min}/2$	6480.48	6482.27





[S-F Yan, P. Zhang, J-W Chen, X_Z Zhang, Y-F Cai, E.N. Saridakis, PRD 101]

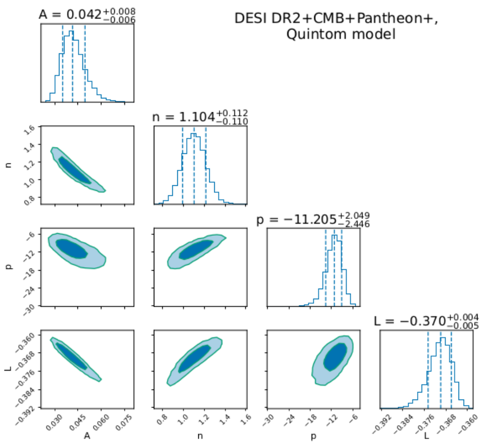
[J-W Chen, W. Luo, Y-F Cai, E.N. Saridakis, PRD 102]

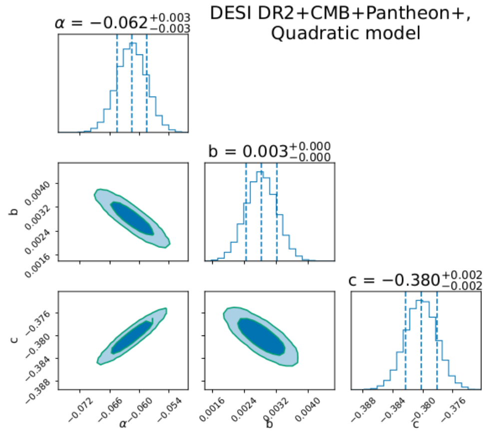
Modified gravity realizations of Quintom after DESI DR2

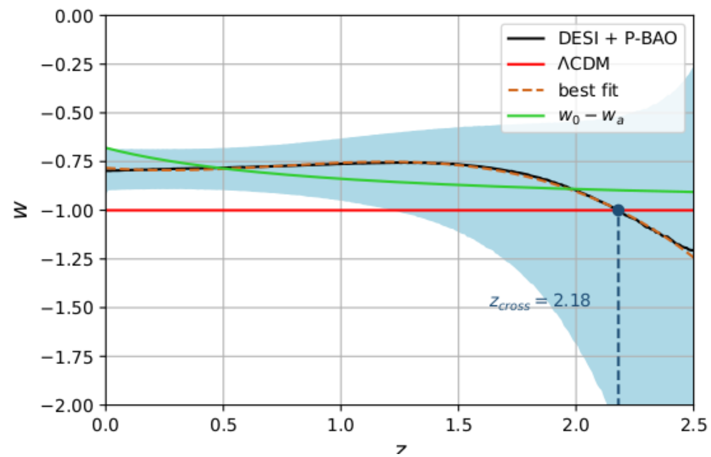
[Z-K Guo, Y-S Piao, X-M Zhang, Y-Z Zhang, Phys.Lett.B 608 (2005)]

$$f(T) = T + \alpha(-T)^n \left[1 - e^{pT_0/T}\right] - 2\Lambda$$

$$\frac{f(T)}{T_0} = \frac{T}{T_0} + \alpha\frac{T}{T_0} + b\frac{T^2}{T_0^2} - 2c$$







DESI DR2+CMB+Pantheon+ datasets		
Criteria	Quintom model	Quadratic model
AIC	97.81	95.146
BIC	117.824	117.1

[Y. Yang, X. Ren ,Q. Wang, Z.Lu, D. zhang, YF. Cai, E. N. Saridakis. Sci.Bull. 69 (2024)]

[Y. Yang, Q. Wang,X. Ren, E. N. Saridakis. YF. Cai, 2504.06784 [astro-ph.CO]]

f(Q) gravity

$$T^{\lambda}{}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} - \Gamma^{\lambda}{}_{\nu\mu}$$
$$R^{\sigma}{}_{\rho\mu\nu} \equiv \partial_{\mu}\Gamma^{\sigma}{}_{\nu\rho} - \partial_{\nu}\Gamma^{\sigma}{}_{\mu\rho} + \Gamma^{\alpha}{}_{\nu\rho}\Gamma^{\sigma}{}_{\mu\alpha} - \Gamma^{\alpha}{}_{\mu\rho}\Gamma^{\sigma}{}_{\nu\alpha} \quad (5)$$

while the nonmetricity can be expressed as

$$Q_{\rho\mu\nu} \equiv \nabla_{\rho} g_{\mu\nu} = \partial_{\rho} g_{\mu\nu} - \Gamma^{\beta}{}_{\rho\mu} g_{\beta\nu} - \Gamma^{\beta}{}_{\rho\nu} g_{\mu\beta} \, . \quad (6)$$

$$Q = -\frac{1}{4} Q_{\alpha\beta\gamma} Q^{\alpha\beta\gamma} + \frac{1}{2} Q_{\alpha\beta\gamma} Q^{\gamma\beta\alpha} + \frac{1}{4} Q_{\alpha} Q^{\alpha} - \frac{1}{2} Q_{\alpha} \tilde{Q}^{\alpha} \, , \quad (7)$$

where $Q_{\alpha} \equiv Q_{\alpha}{}^{\mu}{}_{\mu}$, and $\tilde{Q}^{\alpha} \equiv Q_{\mu}{}^{\mu\alpha}$.

$$S = -\frac{1}{2} \int \mathrm{d}^4 x \sqrt{-g} f(Q). \quad (8)$$

$$\frac{2}{\sqrt{-g}} \nabla_{\alpha} \left\{ \sqrt{-g} g_{\beta\nu} f_Q \left[-\frac{1}{2} L^{\alpha\mu\beta} + \frac{1}{4} g^{\mu\beta} \left(Q^{\alpha} - \tilde{Q}^{\alpha} \right) - \frac{1}{8} \left(g^{\alpha\mu} Q^{\beta} + g^{\alpha\beta} Q^{\mu} \right) \right] \right\}$$
$$+ f_Q \left[-\frac{1}{2} L^{\mu\alpha\beta} - \frac{1}{8} \left(g^{\mu\alpha} Q^{\beta} + g^{\mu\beta} Q^{\alpha} \right) + \frac{1}{4} g^{\alpha\beta} \left(Q^{\mu} - \tilde{Q}^{\mu} \right) \right] Q_{\nu\alpha\beta} + \frac{1}{2} \delta^{\mu}_{\nu} f = T^{\mu}{}_{\nu} \, , \quad (9)$$

with $f_Q = \partial f / \partial Q$.

f(Q) cosmology

$$
\begin{aligned}
6f_Q H^2 - \frac{1}{2}f &= \rho_m, \\
(12H^2 f_{QQ} + f_Q)\dot{H} &= -\frac{1}{2}(\rho_m + p_m)\,. \qquad (11)
\end{aligned}
$$

$$Q = 6H^2, \qquad (12)$$

$$
\begin{aligned}
-a^2\delta\rho &= 6\left(f_Q + 12a^{-2}\mathcal{H}^2 f_{QQ}\right)\mathcal{H}\left(\mathcal{H}\phi + \varphi'\right) + 2f_Q k^2\psi \\
&\quad -2\left[f_Q + 3a^{-2}f_{QQ}\left(\mathcal{H}' + \mathcal{H}^2\right)\right]\mathcal{H}k^2 B\,. \qquad (19)
\end{aligned}
$$

$$
\begin{aligned}
&\frac{1}{2}a^2\left(\rho + p\right)v = \left[f_Q + 3a^{-2}f_{QQ}\left(\mathcal{H}' + \mathcal{H}^2\right)\right]\mathcal{H}\phi \\
&+6a^{-2}f_{QQ}\mathcal{H}^2\varphi' - 9a^{-2}f_{QQ}\left(\mathcal{H}' - \mathcal{H}^2\right)\mathcal{H}\varphi \\
&+f_Q\psi' - a^{-2}f_{QQ}\mathcal{H}^2 k^2 B\,, \qquad (20)
\end{aligned}
$$

$$
\begin{aligned}
\frac{1}{2}a^2\delta p &= \left(f_Q + 12a^{-2}f_{QQ}\mathcal{H}^2\right)\left(\mathcal{H}\phi' + \varphi''\right) + \left[f_Q\left(\mathcal{H}' + 2\mathcal{H}^2 - \frac{1}{3}k^2\right) + 12a^{-2}f_{QQ}\mathcal{H}^2\left(4\mathcal{H}' - \mathcal{H}^2\right) + 12a^{-2}\frac{df_{QQ}}{d\tau}\mathcal{H}^3\right]\phi \\
&+ 2\left[f_Q + 6a^{-2}f_{QQ}\left(3\mathcal{H}' - \mathcal{H}^2\right) + 6a^{-2}\frac{df_{QQ}}{d\tau}\mathcal{H}\right]\mathcal{H}\varphi' + \frac{1}{3}f_Q k^2\psi \\
&- \frac{1}{3}\left(f_Q + 6a^{-2}f_{QQ}\mathcal{H}^2\right)k^2 B' - \frac{1}{3}\left[2f_Q + 3a^{-2}f_{QQ}\left(5\mathcal{H} - \mathcal{H}^2\right) + 6a^{-2}\frac{df_{QQ}}{d\tau}\mathcal{H}\right]\mathcal{H}k^2 B\,, \qquad (21)
\end{aligned}
$$

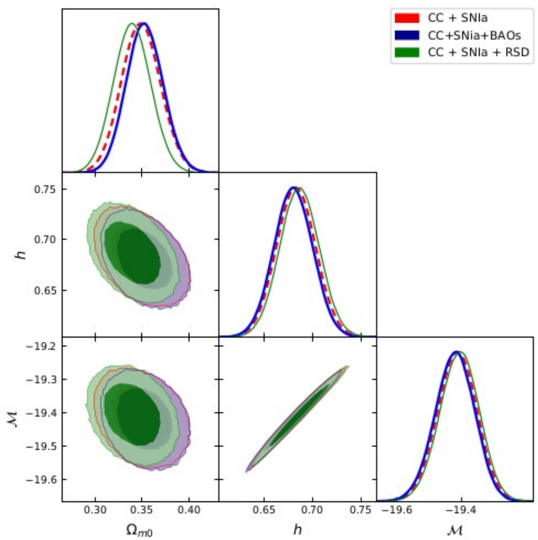
$$
\begin{aligned}
\delta' &= (1 + w)\left(-k^2 v - k^2 B + 3\varphi'\right) + 3\mathcal{H}\left(w\rho - \frac{\delta p}{\rho}\right), \qquad (22) \\
v' &= -\mathcal{H}\left(1 - c_s^2\right)v + \frac{\delta p}{\rho + p} + \phi\,. \qquad (23)
\end{aligned}
$$

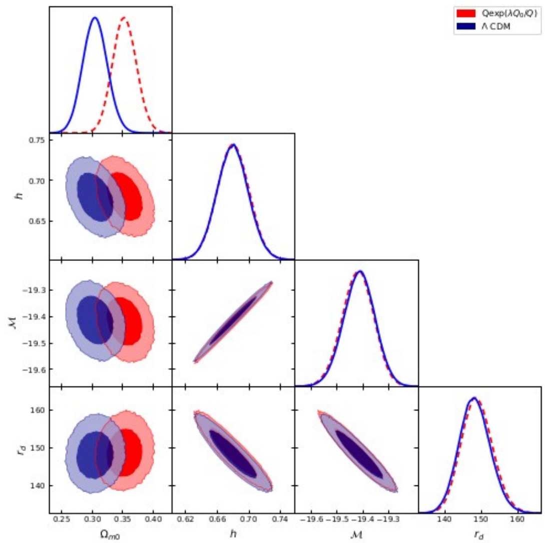
$$
\begin{aligned}
&- f_{QQ}\mathcal{H}\left[2\mathcal{H}\varphi' + \left(\mathcal{H}' + \mathcal{H}^2\right)\phi + \left(\mathcal{H}' - \mathcal{H}^2\right)\left(\psi - B'\right)\right] \\
&- \left[f_{QQ}\left(\mathcal{H}'^2 + \mathcal{H}\mathcal{H}'' - 3\mathcal{H}^2\mathcal{H}' - \frac{1}{3}\mathcal{H}^2 k^2\right)\right. \\
&+ \left.\frac{df_{QQ}}{d\tau}(\mathcal{H}' - \mathcal{H}^2)\mathcal{H}\right]B = 0\,, \qquad (24)
\end{aligned}
$$

$$\delta'' + \mathcal{H}\delta' = \frac{4\pi G\rho}{f_Q}\delta\,, \qquad (30)$$

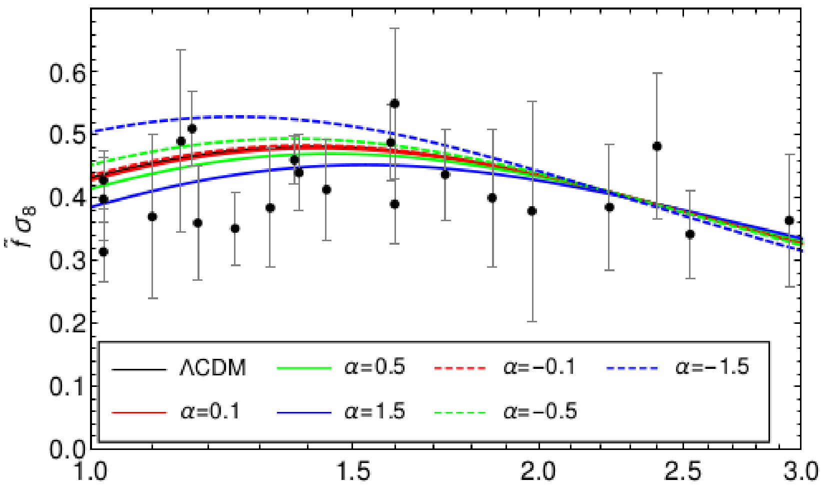
$$G_{eff} \equiv \frac{G}{f_Q}\,, \qquad (31)$$

Solving the tensions in f(Q) gravity





[F. Anagnostopoulos, S. Basilakos, E.N.Saridakis, JCAP 2019]



[S. Peirone, G. Benevento, N. Frusciante, S. Tsujikawa, PRD 100]

Testing GR and Modified Gravity

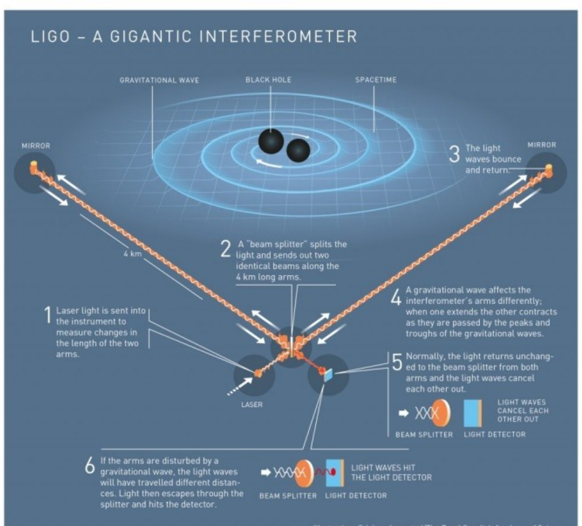
- Solar-System data
- Galaxy data
- Galaxy-cluster data
- Cosmological data (SNIa, BAO,CMB,CC, LSS)
- Early Universe (Inflation, Baryogenesis, BBN)
- Black-Hole-shadow data
- Gravitational-wave data

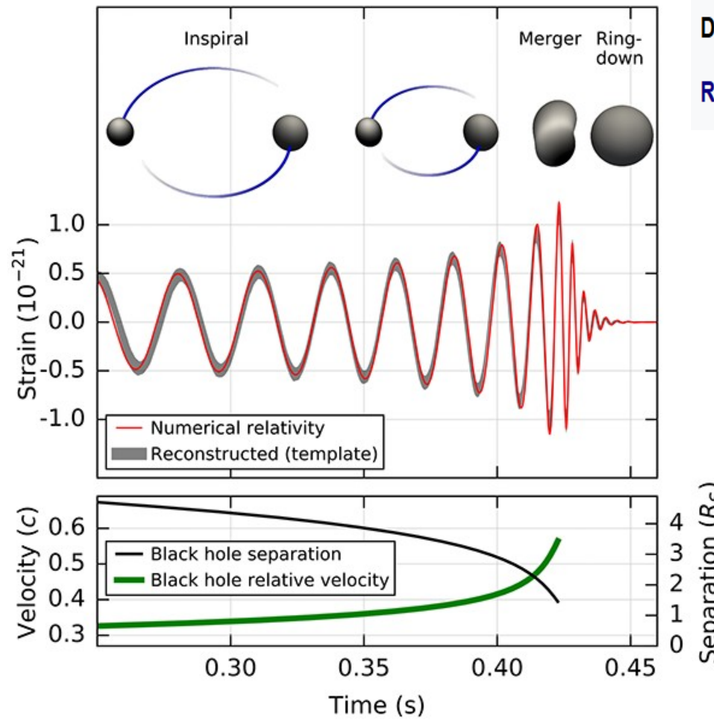
(multi-messenger astronomy)

Gravitational waves

- GW150914: Two black holes w36^{+5}_{-4} M⊙ and 29^{+4}_{-4} M⊙, resulting in a 62^{+4}_{-4} M⊙ black hole

Louisiana.
Washington
4km
10^{-18}m





Distance	410^{+160}_{-180} Mpc
Redshift	$0.093^{+0.030}_{-0.036}$

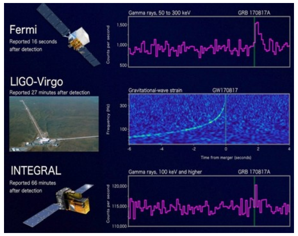
[Abbott et al, LIGO Virgo PRL 116]

2017 Nobel Price in Physics

Gravitational waves

- In case of GWs from black hole mergers we know their properties at the moment of detection, and their direction (in case of three detectors). Assuming GR and ΛCDM we can extract their speed, distance, and properties at the moment of emission.

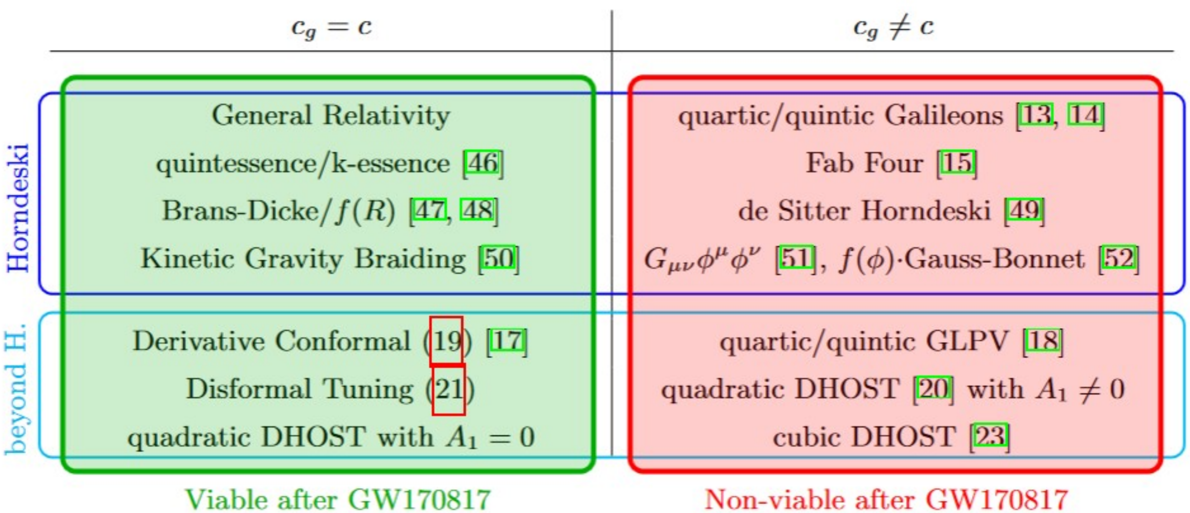
- In case of GWs from neutron star mergers, and their E/M counterpart, we know their properties at the moment of detection and their direction, but using the implied physics from the E/M information we can extract their speed, distance and properties at the moment of emission, independently of the underlying gravitational theory and cosmological scenario.

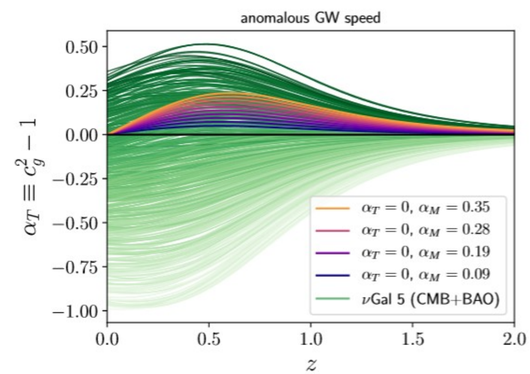


- Great tool for testing General Relativity and cosmological scenarios!

Gravitational waves

- An immediate result: The speed of GWs is equal to the speed of light!
  GW170817 time delay $1.74 \pm 0.05\mathrm{s}$ constrains: $$-3\cdot 10^{-15} \leq c_g/c - 1 \leq 7\cdot 10^{-16}$$
- Excludes a large number of theories that were consistent with other data!





[Ezquiaga, Zumalacarregui PRL 119]

Gravitational waves

- For tensor perturbatior

$$g_{00} = -1\,, \quad g_{0i} = 0\,,$$

$$g_{ij} = a^2\left(\delta_{ij} + h_{ij} + \frac{1}{2}h_{ik}h_{kj}\right)$$

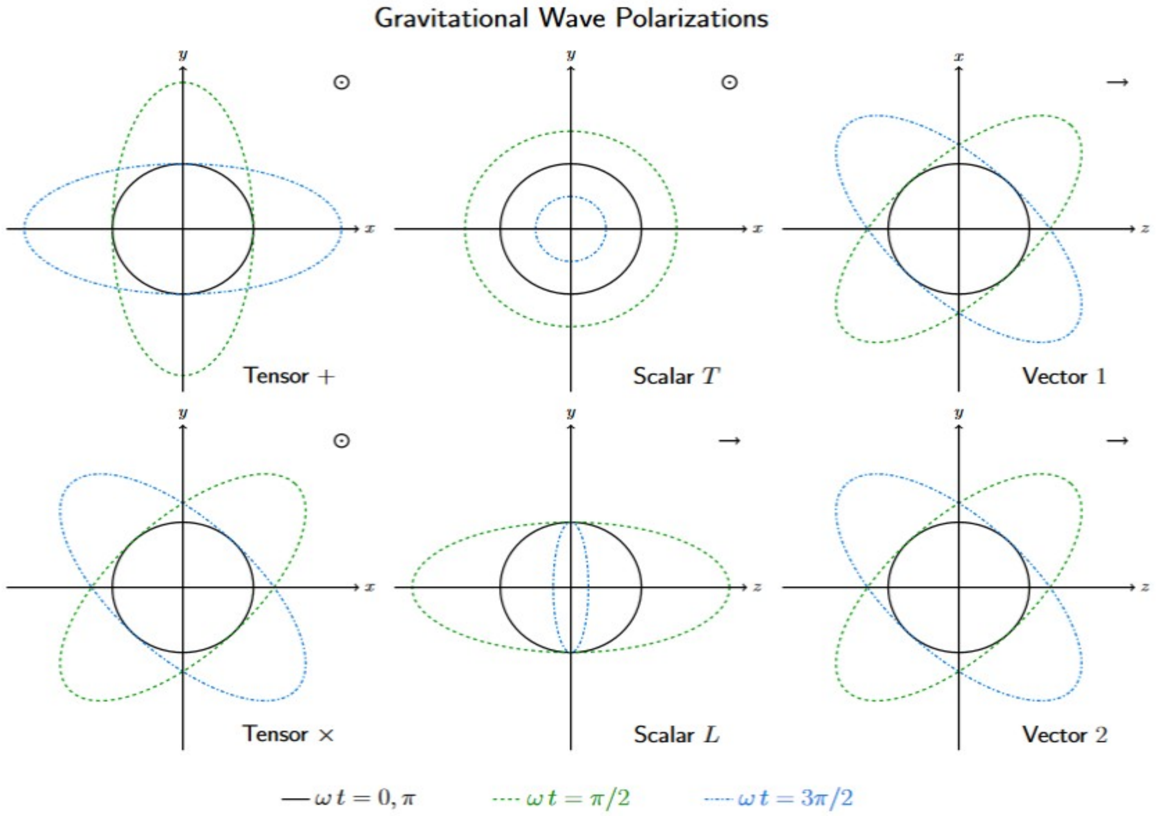
$$\ddot{h}_{ij} + (3 + \alpha_M)\dot{h}_{ij} + (1 + \alpha_T)\frac{k^2}{a^2}h_{ij} = 0$$

$$\alpha_M = \frac{d\log(M_*^2)}{d\log a} \qquad c_g^2 = (1 + \alpha_T)$$

- $$h_{\mathrm{GW}} \sim h_{\mathrm{GR}} \underbrace{e^{-\frac{1}{2}\int \nu \mathcal{H} d\eta}}_{\text{Affects amplitude}} \underbrace{e^{ik\int(\alpha_T + a^2m^2/k^2)^{1/2}d\eta}}_{\text{Affects phase}}$$

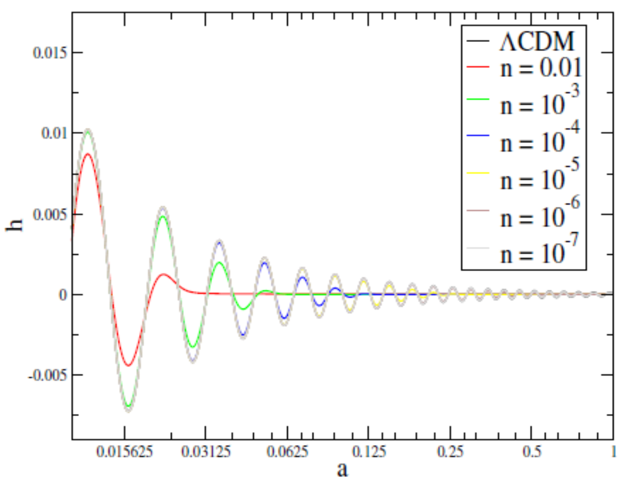
Gravitational waves

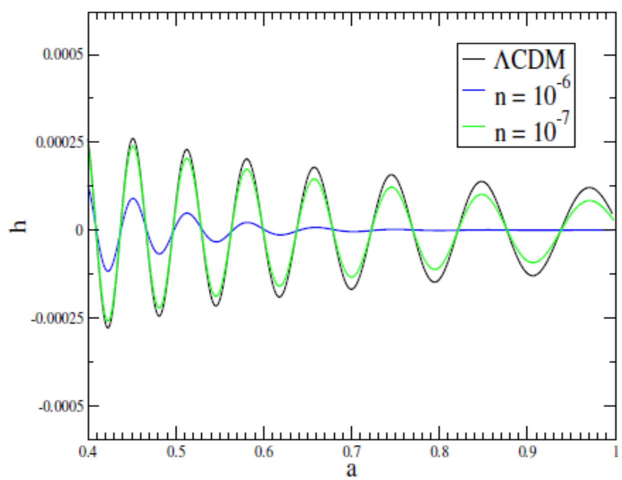
- Polarizations:



Gravitational waves in modified gravity

- Testing General Relativity, modified gravities, and various cosmological scenarios.
- The GWs properties at emission and detection are determined by them.





$$h^{(1)}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 2\gamma_1^{(1)1} & {B_1}^2 \exp(ip_\mu x^\mu) & 0 \\ 0 & {B_1}^2 \exp(ip_\mu x^\mu) & -2\gamma_1^{(1)1} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

[Cai, Li, Saridakis, Xue PRD97]

[Li, Cai, Cai, Saridakis, JCAP 1810]

[Farrugia, Said, Gakis, Saridakis, PRD97]

Gravitational Waves in Modified Teleparallel Theories

- $$S = \frac{1}{16\pi G}\int d^4x\, e\, f(T,B) + \int d^4x\, e\,\mathcal{L}_m \qquad R = -T - 2\nabla^\mu T^\nu{}_{\mu\nu}$$

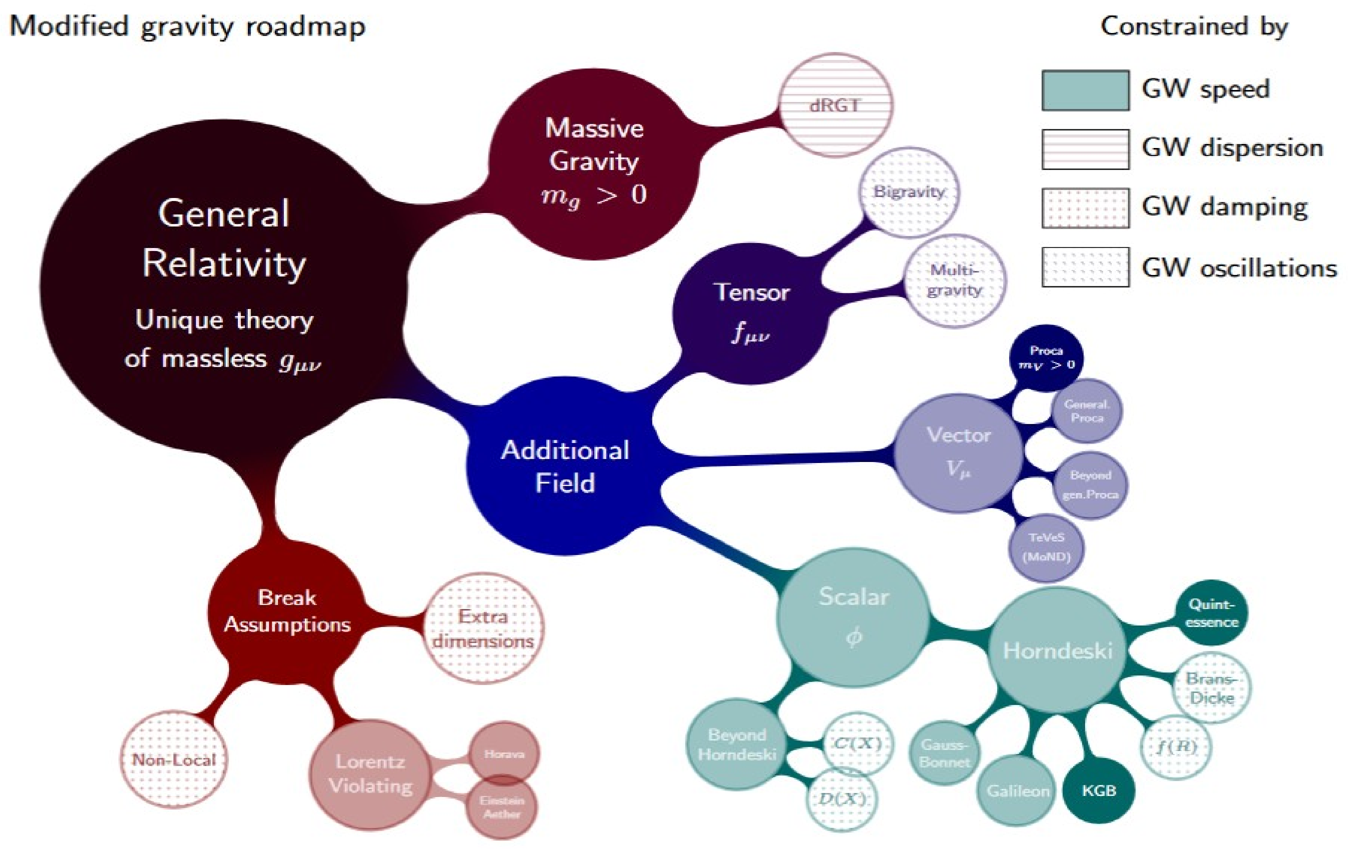
$$\begin{aligned}&- f_T G_{\mu\nu} + \left(g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu\right) f_B\\ &+ \frac{1}{2} g_{\mu\nu}\left(f_B B + f_T T - f\right)\\ &+ 2S_\nu{}^\alpha{}_\mu \partial_\alpha \left(f_T + f_B\right) = 8\pi G\,\Theta_{\mu\nu}\end{aligned}$$

- $$g_{\mu\nu} = \eta_{\mu\nu} + h^{(1)}_{\mu\nu} + \mathcal{O}\left(h^{(2)}_{\mu\nu}\right)$$

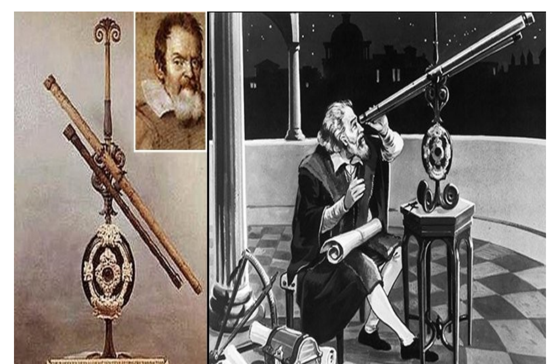
$$h^{(1)}_{\mu\nu} = \begin{pmatrix} -2A\exp(ik_\mu x^\mu) - \frac{f^{(0)}_{BB}B^{(1)}}{f^{(0)}_T} & B_1\exp(ik_\mu x^\mu) & B_2\exp(ik_\mu x^\mu) & -2A\exp(ik_\mu x^\mu) \\ B_1\exp(ik_\mu x^\mu) & h_+ + \frac{f^{(0)}_{BB}B^{(1)}}{f^{(0)}_T} & h_\times & B_1\exp(ik_\mu x^\mu) \\ B_2\exp(ik_\mu x^\mu) & h_\times & -h_+ + \frac{f^{(0)}_{BB}B^{(1)}}{f^{(0)}_T} & B_2\exp(ik_\mu x^\mu) \\ -2A\exp(ik_\mu x^\mu) & B_1\exp(ik_\mu x^\mu) & B_2\exp(ik_\mu x^\mu) & -2A\exp(ik_\mu x^\mu) + \frac{f^{(0)}_{BB}B^{(1)}}{f^{(0)}_T} \end{pmatrix}$$

[Farrugia, Said, Gakis, Saridakis, PRD 97]

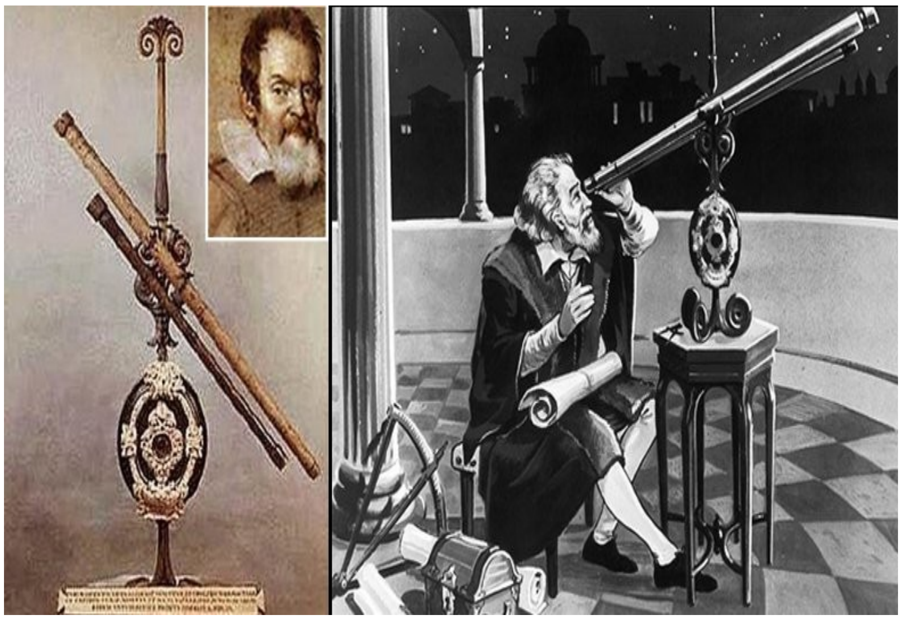
Gravitational waves and Modified Gravity



5000 years of observations
500 years of organized observations



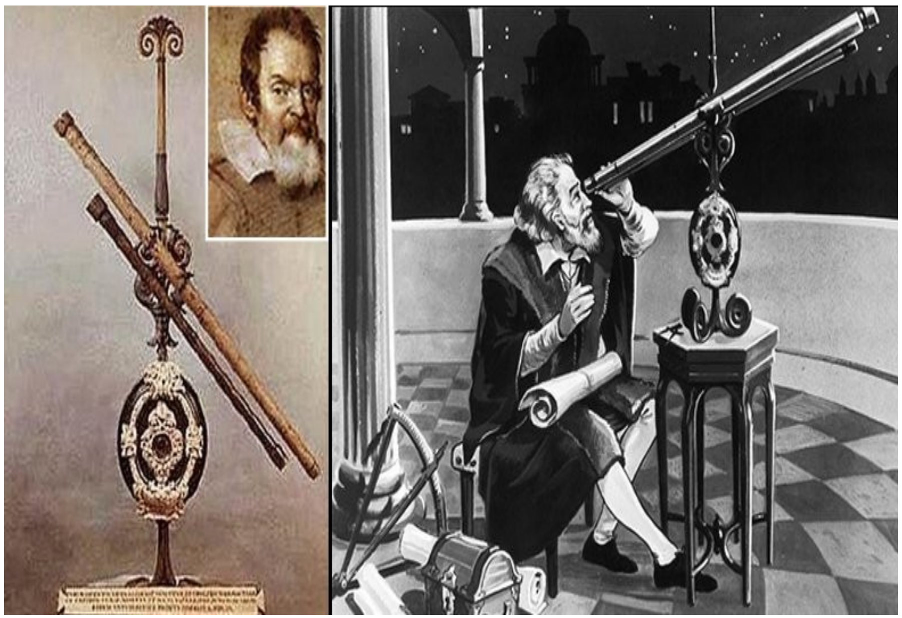
We are approaching a Revolution!



EM observations: 400 years

GW observations: 10 years

We are approaching a Revolution!



EM observations: 400 years

GW observations: 10 years

Thank you!